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CRITICAL METAL CONSUMPTION IN AUTOMOTIVE CATALYSTS - TRENDS AND ALTERNATIVES

PREPARED FOR:

Congress of the United States
Office of Technology Assessment

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CRITICAL METAL CONSUMPTION IN AUTOMOTIVE CATALYSTS

TRENDS AND ALTERNATIVES

Sierra Research
and
Energy and Environmental Analysis, Inc.

DRAFT FINAL REPORT

December 20, 1983

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Section 1

SUMMARY

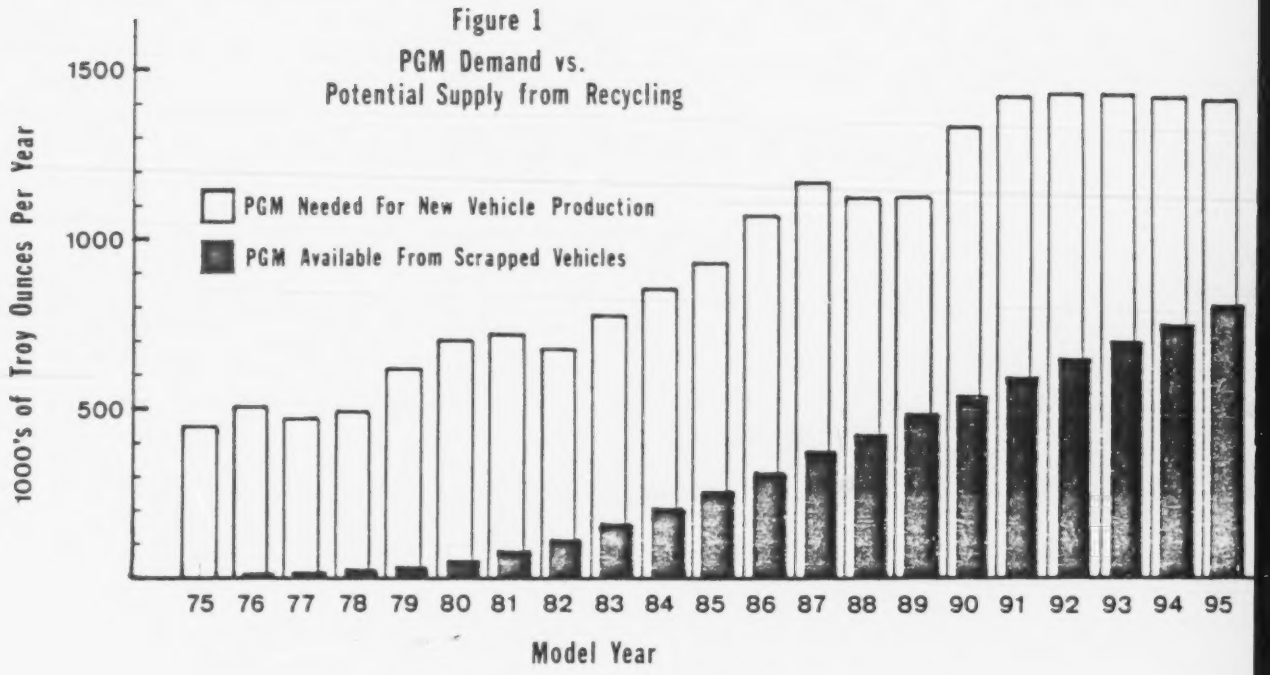
Since the first use of catalysts for automotive emission control on 1975 model year vehicles, the consumption rate of platinum group metal (PGM) in automotive catalysts has risen from about 440,000 to about 800,000 troy ounces per year. At the latter consumption rate, automotive catalysts account for 25-30% of all U.S. imports of platinum, palladium, and rhodium. Chromium use in automotive emission control systems reached a peak of about 12,600 tons per year in 1979 due to high vehicle sales and relatively high usage of large catalyst housings. Reduced sales and increased use of smaller, monolithic catalysts has dropped the current chromium consumption rate to about 10,000 tons per year, 1.5% of U.S. consumption.

The annual use of PGM in automotive emission control systems is expected to increase by about 80% over the next decade. Reduced PGM loadings made possible through the use of improved catalyst technology and the production of lighter weight vehicles will probably be more than offset by increased vehicle sales and the use of PGM in heavy duty vehicles and Diesel particulate traps. Chromium use is expected to return to the 1979 model year consumption rate by 1990 and then increase to about 13,500 tons per year by 1995.

By the mid-1990's, it will be possible for more than half the PGM demand for automotive emission controls to be satisfied through the recycling of PGM from scrapped vehicles. However, catalyst recycling is unlikely to reach its full potential without some assistance such as government education programs directed at the vehicle salvage industry.

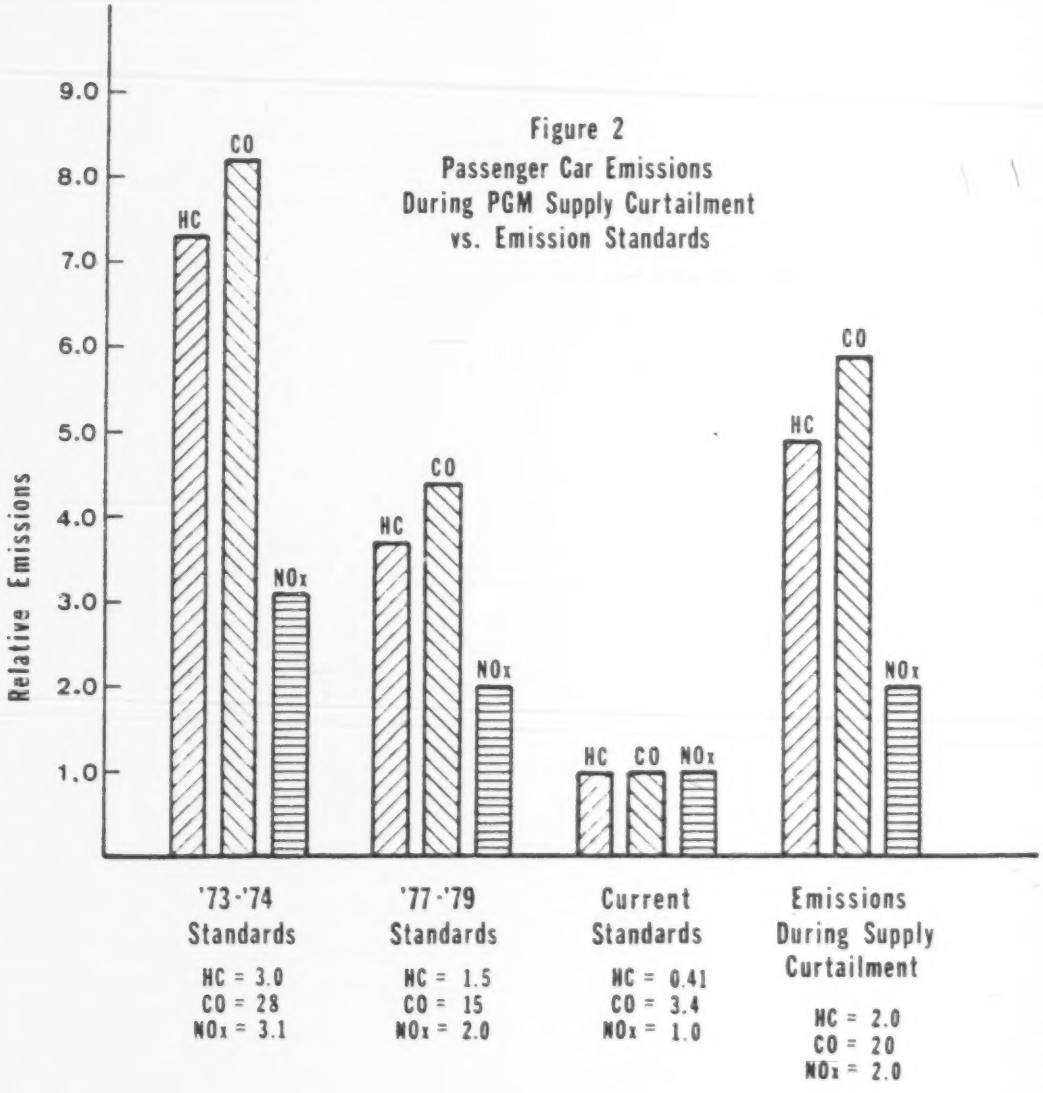
Figure 1 shows the maximum theoretical potential for catalyst recycling compared to the estimated demand for PGM.

Figure 1


PGM Demand vs.
Potential Supply from Recycling
PGM Needed For New Vehicle Production
PGM Available From Scrapped Vehicles
1000's of Troy Ounces Per Year
1500
1000
500
75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
Model Year

All feasible alternatives to the use of PGM for automotive exhaust emissions control have significant adverse impacts. At least in the short term, vehicle emission standards would have to be considerably weakened if PGM use has to be eliminated. Given only one year lead time, manufacturers could not come close to meeting the current passenger car emission standards of 0.41 grams per mile (gpm) hydrocarbon (HC), 3.4 gpm carbon monoxide (CO), and 1.0 gpm oxides of nitrogen (NOx). Without PGM catalysts, the average car would emit about 2.0 gpm HC, 20 gpm CO, and 2.0 gpm NOx. Given about five years' lead time, manufacturers could meet the current emission standards without PGMs but with a fuel economy penalty of approximately 25%. To prevent fuel economy penalties, emission standards would have to be relaxed by more than 100%. However, beyond 1990 it may be possible to significantly reduce the fuel economy penalty associated with meeting the current emission standards without PGM.

Figure 2 illustrates how the temporary emission levels of passenger cars sold during a supply curtailment would compare to current and previous emission standards.



Although automotive catalyst production is forecasted to remain the single largest use of PGM in the U.S., this is one of the few uses which can be immediately interrupted without any measurable effects on the U.S. economy. Vehicles could be delivered without catalysts during a PGM

supply interruption and subsequently retrofitted with catalysts. If such an approach were followed, a short-term lack of progress in improving air quality would occur, but the long-term effectiveness of the automotive emissions control program could be maintained.

Given the importance of PGM to the ability of automobile manufacturers to simultaneously achieve low emissions and high fuel economy, and given the lack of economic disruption associated with a curtailment of PGM use in automotive catalysts, it does not appear reasonable or necessary to vigorously pursue the elimination of PGM from emission control systems. If anything, the reliance on PGM for automotive emission control is <u>increasing</u> the ability of the U.S. to respond to a curtailment of PGM supplies. In the event of a curtailment, PGM use in automotive catalysts could be immediately suspended and PGM from recycled catalysts could be made available for uses which are more critical to the health of the economy. Without the use of PGM for automotive emission control, this resource of PGM would not be available.

The development of alternative technology to meet the emissions standards without the use of PGM would eliminate the possibility of a disruption of the automotive emissions control program. However, the cost of having this technology available for use during a supply curtailment would be substantial. If significant fuel economy penalties are to be avoided, a minimum five-year, all-out effort by the automotive industry would be required. Total costs for the development and tooling of alternative technology systems is impossible to estimate because of the uncertainties involved. Such cost may exceed the resources required to develop U.S. PGM production or to implement a large scale stockpiling program.

# # #

Section 2

INTRODUCTION

At the request of Congress, the Office of Technology Assessment (OTA) is studying the technological feasibility of reducing the dependence of the United States on imported materials which are vital for national defense (strategic) and important to the U.S. industrial economy (critical). Among the critical and strategic materials for which the U.S. is primarily dependent on foreign sources are the platinum group metals (PGMs) and chromium.

Since 1975, the largest single use of PGMs in the U.S. has been for catalytic converters used to control of exhaust emissions from automotive engines. All catalysts used on production passenger cars and light trucks rely on PGMs to promote the oxidation of unburned hydrocarbon (HC) and carbon monoxide (CO) emissions into harmless carbon dioxide (CO_2) and water vapor. In addition, most 1981 and later model cars use PGM catalysts to reduce the concentration of oxides of nitrogen emissions. A significant amount of chromium is also used in the housings of catalytic converters because the catalyst occasionally operates at temperatures which are too high for low grade carbon steels. Chromium containing steels also eliminate the possibility that corrosion will cause a leakage of untreated exhaust gas during the 5 yr./50,000 mile period during which manufacturers are responsible for the emissions performance of properly maintained vehicles in customer service.

Purpose of the Study

This study of critical metals use in automotive catalysts was commissioned in support of OTA's overall assessment of "Technologies to Reduce U.S. Materials Impact Vulnerability." The purpose of this study was to provide an analysis of the current and future dependence of the automotive emission control program on PGMs and chromium. Included in the analysis is an assessment of the feasibility of reducing the amount of "primary" PGM required for automotive emission control through converter recycling and alternative technology. In addition, OTA requested an assessment of the options available for responding to a supply curtailment of PGM. To accomplish the study objectives, four basic tasks were required:

1. Estimate historical and future PGM and chromium consumption trends.

2. Evaluate catalyst recycling potential.

3. Analyze alternative to PGMs for automotive emission control.

4. Identify possible responses to a PGM supply curtailment.

Description of the Work Program

Numerous references in the technical literature address the PGM and chromium usage in catalysts, catalyst recycling, and alternatives to PGMs for automotive emission control. However, much of this literature has been outdated by advancements in emission control technology and changes in vehicle size and sales trends. In addition, previous attempts to quantify PGM use in automotive catalysts have been

frustrated by the fact that vehicle manufacturers generally consider PGM usage to be proprietary information.

Previously published studies related to the required tasks were used to the maximum extent possible; however, considerable additional information was obtained. PGM and chromium usage data were updated based on interviews with vehicle manufacturers and catalyst vendors, and from an analysis of proprietary data obtained under a confidentiality agreement, regarding the PGM content of catalysts. Production volumes for catalytic converters were based on historical sales data and future sales forecasts from an econometric model used for forecasting fuel demand by the U.S. Department of Energy.

Available literature on catalyst recycling potential was supplemented with the latest information available on PGM usage and interviews with companies with recycling technology. Previously published information on technological alternatives to the use of PGMs for exhaust emission control was supplemented with vehicle manufacturer interviews.

No published literature was identified regarding the possible responses to a curtailment of PGM supplies. Supply curtailment scenarios were developed based on the assessment of alternative technologies and manufacturing lead time considerations. The opinions of automobile manufacturers and the staff of the U.S. Environmental Protection Agency and the California Air Resources Board were also considered.

Schedule and resource constraints did not permit the development of the most refined estimates of current and future PGM and chromium use possible. For example, insufficient time was available to solicit and obtain much information directly from foreign vehicle manufacturers. The authors do not

consider this lack of refinement significant given the large uncertainties in future PGM use which are associated with factors that are impossible to forecast precisely, such as future vehicle sales, PGM costs, Diesel penetration, and technological innovation.

Organization of the Report

The following section of this report (Section 3) contains the major conclusions reached by the study team regarding each area of the study: consumption trends, recycling, alternative technologies, and supply curtailment response. Section 4 contains the detailed information developed on PGM and chromium consumption trends. Section 5 contains the detailed discussion of catalyst recycling potential. Section 6 contains the analysis of technological alternatives to the use of PGMs for automotive emission control. Section 7 covers the possible ways of dealing with PGM supply curtailments. Section 8 lists the references used during the study.

Section 3

CONCLUSIONS

Based on the results of the study the authors conclude:

1. Platinum group metal requirements for automotive catalysts were typically 480,000 troy ounces per year for the production of 1975 through 1978 model passenger cars and light trucks. This volume of PGM use represented approximately 24% of the total U.S. imports of platinum, palladium, and rhodium. During these model years, 87% of the gasoline engine powered passenger cars and 77% of the gasoline engine powered light trucks were catalyst equipped. The average catalyst equipped vehicle used 0.06 troy ounces of PGM. About 70% of the total PGM used in catalysts for 1975 through 1978 model vehicles was platinum and the balance was mostly palladium. Less than 1% of the total PGM used during these model years was rhodium.

2. For the 1980 to 1983 model years, average PGM usage for each catalyst equipped vehicle increased by approximately 33%, to about 0.08 troy ounces, due to the imposition of more stringent exhaust emission standards. In addition, catalyst usage increased to almost 100% for both passenger cars and light trucks which use gasoline engines. Total vehicle sales declined during this time period; however, the size range of light trucks subject to catalyst-forcing emission standards were extended in 1979. All factors combined resulted in an increase in total PGM consumption in catalysts to about 720,000 troy

ounces per year during this time period, about 25% of total U.S. imports of platinum, palladium, and rhodium in 1980. Platinum remained the principal active ingredient of automotive catalysts, representing 68% of total PGM. Rhodium increased to 7% of total PGM as a result of the need for the catalytic control of oxides of nitrogen (NOx) emissions. Palladium use declined on a percentage basis to about 25% of total PGM.

3. Between now and 1989, PGM use is expected to remain essentially constant on a per vehicle basis. PGM loading reductions made possible through the use of improved catalyst formulations will probably be offset by the interest on the part of EPA and vehicle manufacturers in improving the in-use performance of catalyst equipped cars and trucks. Total PGM use in automotive catalysts is expected to increase to about 1,100,000 troy ounces per year, due to increased sales of passenger cars and light trucks. Increased stringency of NOx emission standards for light trucks during this time period is expected to increase the rhodium percentage of the total PGMs used in catalysts to about 10%.

   During the 1984 to 1989 time period, the percentage of cars and light trucks using Diesel engines is likely to increase; however, about half of the Diesel powered vehicles are expected to use particulate trapping systems. It is estimated that at least half of the traps used on Diesel powered vehicles are likely to contain PGMs. Also offsetting the reduction in the percentage of gasoline powered passenger cars and light trucks is likely to be increased use of catalysts on heavy duty gasoline engines.

4. Beyond 1989, PGM use in automotive catalysts is expected to be further increased due to the use of particulate

traps on heavy duty vehicles and increased vehicle sales. However, significant potential exists for all of this post-1989 increase in PGM use to be eliminated due to the fact that improved catalysts are likely to be available which achieve adequate performance with lower PGM loadings. The feasibility of catalysts with lower loadings of PGM will be further increased if leaded gasoline has been eliminated from the distribution system.

5. Chromium usage in the containers for automotive catalysts from the 1975 to 1984 model vehicles has dropped from about 2.6 to about 1.8 pounds per catalyst equipped vehicle. At the sales volume estimated for the 1983 model year, this represents an annual consumption of 9,644 tons per year, or about 1.5% of total U.S. chromium consumption. Due to higher vehicle sales and the use of larger catalyst containers, 1979 model vehicles used about 12,600 tons per year of chromium. No substitutes for the 409 stainless steel used in converters are expected to be available in the foreseeable future, and the automotive industry does not appear to place a high priority on research and development programs to reduce the chromium content of converter housings. Continuing trends toward the reduction of vehicle weight, increased sales of inline engines, and reduced use of large, pelletized catalysts will reduce the average per vehicle use of chromium in automotive catalysts in the future. However, increased vehicle sales and increase catalyst usage is estimated to soon increase annual chromium usage in automotive catalysts to 11,000 tons per year. By 1995, chromium consumption is estimated to rise to 13,500 tons per year due to more stringent emission standards for heavy duty vehicles.

6. The industrial capacity necessary to recycle all automotive catalysts is <u>already</u> available. The

technological feasibility of recycling automotive catalysts has been clearly demonstrated and limited recycling is already underway. Increased recycling will undoubtedly occur as significant numbers of the 1975 and later model year vehicles are scrapped. However, the extent to which automotive catalysts will be recycled is highly uncertain.

The cost of recovering PGMs from used automotive catalysts would be lower than the cost of refining PGMs from ore, even if the loading of the average catalyst was substantially reduced. However, the cost associated with salvaging the catalysts and transporting them to recycling facilities can exceed the value of the catalyst to a recycler unless the salvaging and transportation is done in a very organized and efficient manner. In addition, a significant percentage of vehicles, perhaps 20%, are salvaged through the practice of whole vehicle shredding without salvaging of individual components, such as the catalyst. The necessary changes in salvage operations to maximize the extent to which catalysts are recycled represents a significant change in many salvage operations which may not occur because of the inertia in the system. Government sponsored educational programs in the recycling area may be an effective means of overcoming this inertia and reducing the dependence of the U.S. on PGM imports while contributing to increased economic activity.

If the recycling of automotive catalysts reaches 90% of its theoretical potential, then the imported PGMs required for automotive catalysts will eventually be reduced by more than 50%.

7. Technology is available to eliminate the use of PGMs for automotive emission control but only with a major loss of

fuel economy or a major relaxation of the automotive emission standards. With no change in emission standards, PGMs could be eliminated from automotive emission control systems given about five years lead time to develop thermal reactor based control systems. However, chromium requirements for automotive emission control systems would not be reduced since the thermal reactors would utilize stainless steel. The cost of thermal reactor-based emission control systems would be comparable to catalyst systems; however, a fuel economy penalty of about 25% would be expected. Relaxation of the carbon monoxide standard from 3.4 to 7.0-15.0 grams per mile would reduce the economy loss associated with noncatalyst systems to about 15%. To eliminate any loss in fuel economy while eliminating catalysts, emission standards would have to be relaxed to the 1977-1979 standards of 1.5 grams per mile hydrocarbons (HC), 15 grams per mile carbon monoxide (CO), and 2.0 grams per mile of oxides of nitrogen (NOx). These levels represent increases in emissions compared to the current standards of 266% for HC, 341% for CO, and 100% for NOx.

Given more than five years' lead time, progress could be expected in reducing the fuel economy penalty associated with meeting the current emission standards without the use of PGMs. Improved base metal catalyst formulations might become available and progress could be made in the development of ceramic components for the conservation of exhaust heat necessary to thermally oxidize HC emissions. The development of production-feasible ceramic components would also reduce the need for chromium use.

Regarding engines that can meet the current emission standards without PGMs and without fuel economy penalties, the Diesel engine is the only practical alternative to the conventional Otto cycle, gasoline engine through at least 1995. The control of Diesel

particulate emissions may be most practically achieved with the use of PGM catalyzed traps, however, non-catalytic, trap systems are also technologically feasible. Numerous economic and institutional factors will prevent the Diesel from becoming the principal automotive powerplant by 1995, barring government intervention.

To avoid the relaxation of emission standards or fuel economy penalties, an effective government action to reduce the use of PGMs in automotive catalysts could be the total prohibition of lead additives in all grades of gasoline. Trace lead contamination of commercially available unleaded fuel currently prevents reductions in catalyst loadings that would otherwise be feasible.

8. An unplanned for supply curtailment of PGM would almost immediately disrupt the automotive emission control program. Stockpiles of PGM intended for catalyst use would be exhausted in 3 to 6 months. During the first year of a supply curtailment, it would be impractical for the government to attempt to enforce any specific set of emission standards. Because of the high level of model to model variability in non-catalyst emission levels, standards which could be met by most vehicles would have to be set at ten times the level of the current HC and CO standards, and four times the NOx standard. Average non-catalyst emission levels would be about five times the HC and CO standards and double the NOx standard.

   The most reasonable approach for dealing with a PGM supply interruption in the short term would be for the government to allow the sale of vehicles that are identical to their certified configuration, except for the replacement of the catalytic converter with a removable section of straight pipe. Such pipes could be produced

in sufficient quantities before the limited supply of catalysts was exhausted. Vehicle manufacturers should then be required to recall and retrofit vehicles with catalysts when the supply curtailment has ended. The price of the non-catalyst cars could be increased by an amount sufficient to cover the cost of the recall campaign and some inducement to ensure a high rate of retrofit. Amendments to the Clean Air Act would be required to implement this alternative.

9. For PGM supply curtailments lasting between one and three years, the retrofit approach could be modified to include the recalibration of vehicles for lower non-catalyst emissions. Fuel metering systems could be programmed for somewhat leaner operation to reduce HC and CO emissions. At the expense of some fuel economy loss, spark advance calibrations could be retarded for further control of HC and NOx. Average emission levels approximately equal to the 1977-1979 standards of 1.5 HC, 15 CO, and 2.0 NOx could be achieved under such an approach. However, the standard would have to be applied to the average emissions of a manufacturer's production because of model to model variability and the lack of lead time to redesign models with relatively high non-catalyst emission levels. Vehicles certified under such an approach would also require recalibration when eventually recalled and retrofitted. Since most systems are now "computer controlled", reprogramming could be as simple as the replacement of a chip within the electronic control unit. However, it will probably be more practical for car dealers to replace the entire electronic control unit.

Unless a supply curtailment lasted for more than two years, the catalyst retrofit approach would be extremely attractive. In the immediate future, there would not be

a significant increase in emissions associated with such a program because the emissions of the non-catalyst new cars would not be significantly different from the emissions of the older vehicles which are retired from service or driven less as the result of new vehicles entering the fleet. When retrofitted, the automotive emission control program would be back on track, and emissions would be just as low as if the supply curtailment had never occurred.

The response to longer term curtailments of PGM would have to consider the capability of alternative technology if a significant adverse effect on the emissions control program is to be prevented. Lean burn engines incorporating improved fuel metering and thermal reactors appear to have significant potential. In conjunction with heat conservation techniques and fast-burn combustion chambers, it may be possible to approach or meet the current emission standards without a fuel economy penalty by using such technology. However, a minimum of five years would be required to develop and mass produce such control systems.

Currently available non-catalyst technology appears limited to emission standards about equal to the 1977 standards (1.5 HC, 15 CO, 2.0 NOx), if significant fuel economy penalties are to be avoided. About four years lead time would be required to mass produce such systems.

The suggested options for the response to a longer term supply curtailment would also require Clean Air Act amendments.

Section 4

CONSUMPTION TRENDS

The first use of catalysts on production automobiles began in the fall of 1974 with the introduction of the 1975 model year passenger cars and light duty trucks. The percentage of new vehicles equipped with catalysts has increased since 1975 and additional applications are anticipated in the future. Estimates of the total PGM and chromium used for the production of automotive catalysts have been made for the twenty one model years from 1975 through 1995.

Historical Consumption Trend

Data Sources and Methodology - Calculation of the amount of PGMs and chromium thus far used in the production of automotive catalysts requires data regarding the sales, catalyst loading, and chromium usage for each vehicle model which is catalyst equipped. The arithmetic required is simple enough but all of the necessary data have never been published. Most manufacturers designate the loading of their catalysts as confidential, and sales data are not generally disaggregated based on catalyst use. Previous estimates of PGM and chromium use in catalysts have been based on estimates of PGM and chromium use and the sales of catalyst equipped vehicles.

Although manufacturers continue to designate the amount of PGM used in catalysts as confidential, it is a relatively simple matter to determine the amount of PGM contained in a

particular catalyst through chemical analysis. The results of such analyses and voluntary disclosure of catalyst loading information frequently appear in the technical literature.(1,2,3)* In addition, under confidentiality agreements, most of the PGM loading data for 1982 model passenger cars and some of the data for other model years were obtained.

To supplement the data available from confidentiality agreements and literature review, Sierra Research requested model year specific data from General Motors, Ford, and Chrysler regarding these manufacturers' average PGM usage for passenger cars and light duty trucks produced from 1975 through 1983 and planned for 1984 production. All three manufacturers provided the requested data.(4,5,6) Since American Motors used GM catalysts for most of its production during the 1975 to 1984 time period, very accurate estimates of PGM use in vehicles representing over 70% of U.S. production were available to the study team.

The schedule and resources for the study did not permit consultation with foreign manufacturers in an attempt to obtain precise information regarding the historical use of PGM in catalyst equipped imported vehicles. PGM usage on imported passenger cars was accurately determined only for the 1982 model year since confidential catalyst descriptions for this model year were available. For trucks and for other model years, the PGM usage in imported vehicles was estimated based on a more limited data base. This data base included information obtained from the literature review and limited confidential information available to the study team.

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*Numbers in parenthesis designate references listed in Section 8.

Data on the amount of chromium typically used in automotive catalysts was based on previously published estimates, (7,8) one of which relied on weight measurements from a variety of disassembled catalysts obtained from scrapped vehicles. These previously published estimates were verified through consultation with General Motors and Ford.

Details regarding the calculation of historical PGM and chromium consumption trends is contained in Appendix 1.

Annual consumption of PGM in all automotive catalysts is shown in Table 1 and Figure 3. The combination of catalyst usage fractions and vehicle sales volumes resulted in a total annual consumption of 446,000 troy ounces per year beginning with the 1975 model year. An increased percentage of catalyst equipped vehicles and increased vehicle sales caused PGM consumption to increase to 502,000 troy ounces in the 1976 model year despite a slight reduction in the average PGM content per catalyst. Further reductions in catalyst loadings caused annual consumption to drop below 500,000 troy ounces in 1977 and 1978, even though total vehicle sales and the percentage of vehicles equipped with catalysts increased. A typical value for this time period is 480,000 troy ounces per year, which is about 24% of total U.S imports of platinum (Pt), palladium (Pd), and rhodium (Rh), during the same time period (7).

PGM consumption jumped to about 618,000 troy ounces during the 1979 model year, primarily due to the fact that the light duty truck class was expanded to cover vehicles up to 8,500 pounds GVW instead of only those trucks of 6,000 GVW and less. A large increase in trucks subject to emission standards requiring catalytic controls therefore occurred.

More stringent emission standards for passenger cars caused PGM consumption to increase to approximately 700,000 troy

Table 1

Historical PGM Consumption
in Automotive Catalysts

Model Year	-- Gas Cars -- Average PGM Usage*	Sales (1000's)	-- Gas Trucks -- Average PGM Usage*	Sales (1000's)	-- PGM Consumption -- (1000's of Troy Ounces) Pt	Pd	Rh	Total
1975	.049	8,186	.037	1,210	316.6	129.3	0.0	445.9
1976	.046	9,732	.037	1,470	356.4	145.6	0.0	502.1
1977	.039	10,797	.043	1,190	335.3	136.9	0.0**	472.3
1978	.041	10,859	.041	1,120	348.7	142.4	0.0**	491.1
1979	.047	10,513	.045	2,742	438.4	179.1	0.0**	617.5
1980	.072	8,488	.048	1,943	500.1	204.2	0.0**	704.4
1981	.078	8,163	.051	1,664	493.3	183.8	44.6	721.6
1982	.077	7,599	.052	1,913	464.5	172.2	48.0	684.6
1983	.076	8,606	.055	2,109	529.0	187.2	53.9	770.1

*troy ounces per vehicle including non-catalyst vehicles.
**limited use of 3-way catalysts ignored.

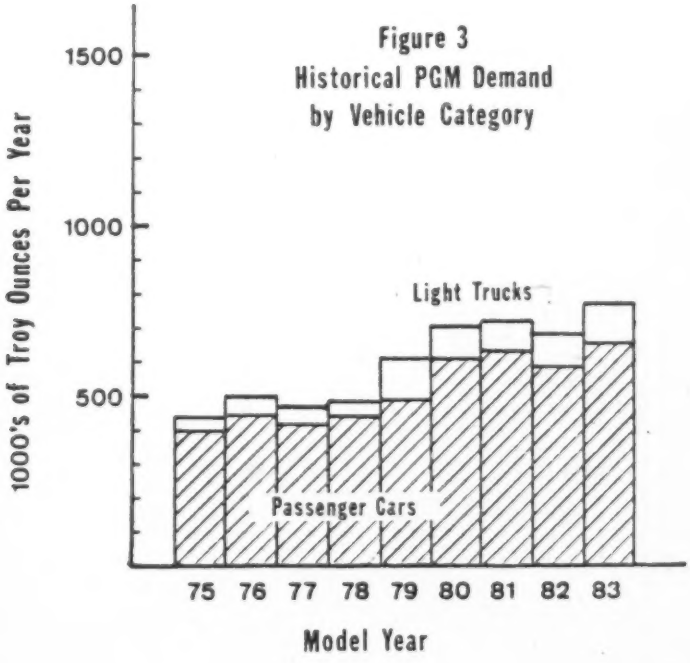


Figure 3
Historical PGM Demand
by Vehicle Category

ounces per year for the 1980 through 1982 model years even though vehicle sales volumes dropped significantly. The significant increase in sales which occurred during the 1983 model year has pushed PGM consumption in automotive catalysts to an all time high of 770,000 troy ounces per year. This consumption level represents 27% of total U.S. imports of platinum, palladium, and rhodium for 1980, based on data reported in reference 7.

Estimates of chromium consumption in automotive catalysts are shown in Table 2. As shown in the table, there has been a significant drop in the amount of chromium used in the average catalyst system since 1975. This is due to two factors: 1) a decline in the percentage of Vee configuration engines (from about 60% to about 35% between 1975 and 1983); and 2) a decline in the percentage of catalyst cars using pelletized converters.

The table also shows that when the fluctuations in annual sales are factored in, chromium consumption peaked in 1979 at about 12,600 tons per year. Chromium consumption subsequently dropped to under 10,000 tons per year due to reduced sales, reduced pelletized catalyst use, and a reduced percentage of Vee engines.

Future Consumption Trends

The future consumption of PGM and chromium for automotive catalysts will depend on many factors, including total vehicle sales, stringency of emission standards, advancements in catalyst technology, and increased use of alternative technologies which are not dependent or are less dependent on PGM for emission control. To forecast future PGM use with reasonable accuracy, it is necessary to quantify the effect of these factors based on a detailed

analysis of the current data base in conjunction with projections of future technology use, vehicle sales, and emission standards.

Table 2

Historical Chromium Consumption
in Automotive Catalysts

Model Year	Pounds Chromium/ Catalyst	Gasoline ----- Cars ------ Catalyst Fraction	Gasoline ----- Cars ------ Sales (1000's)	Gasoline ---- Trucks ----- Catalyst Fraction	Gasoline ---- Trucks ----- Sales (1000's)	Annual Chromium Usage (tons)
1975	2.6	.794	8,186	.746	1,210	9,623
1976	2.4	.890	9,732	.743	1,470	11,705
1977	2.3	.877	10,797	.851	1,190	12,053
1978	2.2	.897	10,859	.814	1,120	11,717
1979	2.1	.913	10,513	.890	2,742	12,641
1980	2.0	.951	8,488	.953	1,943	9,924
1981	1.9	1.000	8,163	1.000	1,664	9,336
1982	1.9	1.000	7,599	1.000	1,913	9,036
1983	1.8	1.000	8,606	1.000	2,109	9,644

Factors Currently Affecting PGM Use - Although the summary of the catalyst loading data presented in earlier tables does not indicate a major difference between manufacturers, our analysis of catalyst loadings for individual foreign manufacturers and individual models produced by domestic manufacturers indicated major differences between some of the models. In fact, the amount of PGM used on the 1982 model passenger cars varied over a range of more than 10:1. The most heavily loaded catalysts used 0.33 troy ounces, while the most lightly loaded catalysts used only 0.03 troy ounces.

There are also major variations in the types of PGM on late model cars. Some models use no palladium. Some oxidation catalyst equipped models use only palladium. Some 3-way catalysts use very little rhodium, while others are heavily loaded with this element.

Based on the review of historical catalyst loading data, it is apparent that the amount of PGM required for catalysts depends in part on vehicle weight. Lighter weight vehicles tend to emit lower levels of exhaust emissions, and they therefore require less catalytic emission control to meet emission standards. Weight alone, however, does not account for much of the difference between models.

There are many reasons for the differences which exist between the amount of PGM used on the various late model cars. An understanding of the reasons for the differences is necessary in order to project future PGM use.

One technology variable that exists within late model cars is the design of the emission control system itself. There are fundamental differences between catalyst equipped vehicles. One obvious difference is that some models are equipped with oxidation catalysts, some with 3-way

catalysts, and some with both 3-way and oxidation catalysts. However, there are many significant emission control system differences within these groupings by catalyst type.

Some vehicles use exhaust gas recirculation (EGR) for the control of NOx emissions, while others rely exclusively on the catalytic control of NOx. Some of the EGR systems are controlled in a sophisticated manner and some are not. Some vehicles, even vehicles equipped with 3-way catalysts, use conventional carburetors without "feedback control" of the air/fuel ratio, while most carburetor equipped 3-way vehicles incorporate an exhaust oxygen sensor and closed-loop control to hold the air/fuel ratio very close to stoichiometry (about 14.7:1) under most operating conditions. Other vehicles use fuel injection instead of carburetors. Some vehicles use various types of exhaust air injection.

Statistical analysis of the catalyst loading and control technology specifications for the 1982 models indicated that, at the 90% confidence level, certain control technology combinations were related to PGM use. For example, in vehicles incorporating 3-way catalysts, low palladium loadings and high rhodium loadings were associated with the use of multipoint fuel injection systems. Low platinum use, low rhodium use, and high palladium use were associated with the use of oxidation catalysts. There is also a clear difference in the type of catalyst needed to meet the federal light truck emission standards, the federal and California passenger car standards, and the California truck standards. Less expensive oxidation catalysts are used on the overwhelming majority of light trucks designed to meet the federal standards, while the level of the passenger car standards and the California truck standards result in the use of primarily 3-way catalyst and 3-way plus oxidation catalyst systems.

Some of the PGM use/technology relationships which appeared to have statistical significance make sense technically but others do not. For example, the technical literature indicates that, per gram of PGM used, the most effective oxidation catalysts are those which use platinum and palladium in a ratio of 1:3. However, 3-way catalysts seem to be more effective with low palladium use and high rhodium use in conjunction with platinum. Oxidation catalyst equipped vehicles would therefore be expected to be different from 3-way catalyst vehicles in terms of the type of PGM use.

However, the literature also indicates that multipoint fuel injection systems tend to provide improved 3-way catalyst efficiency. Why then should vehicles equipped with multipoint fuel injection systems use more PGM? The answer has nothing to do with the relationship between multipoint fuel injection use and the need for high PGM loadings. Multipoint fuel injection just happens to be used principally by manufacturers who have been extremely conservative in the design of their emission control systems. Manufacturers who use multipoint fuel injection in conjunction with heavily loaded catalysts have significantly lower emission levels than those who do not.

Emission control technology differences also do not explain why some models required more than 10 times the amount of PGM used in other models. However, the models with the highest PGM loadings appear to be "outliers". They are significantly higher than the majority of the vehicles. The need for such extremely high PGM loadings are most likely due to the fact that these vehicles use "problem" engines. Intake manifold and combustion chamber geometry incorporated into these engines are probably not conducive to low non-catalyst emission levels.

In light of the complexity in the relationship between PGM use and technology variations in gasoline engines, considerable engineering judgement had to be exercised in developing forecasts for future PGM use. Auto manufacturers, catalyst vendors, and EPA staff were consulted to assist the study team in formulating such judgements. The conclusions reached were as follows:

- 3-way catalysts will be the dominant catalyst choice whenever emission standards require as much control as the current passenger car standards or the California light truck standards.

- Catalysts containing the highest PGM loadings will soon be phased out of production as older engine designs are replaced.

- Catalysts used on vehicles with multipoint fuel injection will continue to use higher PGM loadings due to conservatism by some manufacturers and due to renewed interest in high performance engines which are likely to require increased catalytic emission control.

- Some reduction in catalyst loading will be possible as a result of weight reductions anticipated for future cars and trucks.

- Further catalyst loading reductions made possible through the continuing advancements in catalyst technology will be offset by some manufacturers' needs to achieve improved in-use emission performance.

To quantify the future relationships between PGM use and vehicle weight, an analysis of the 1982 model year data was performed as described in Appendix 2.

It should be noted that there is significant uncertainty associated with the concensus opinion developed regarding the future use of PGM in automotive catalysts. Vehicle sales, for example, have historically proven difficult to forecast. Another disruption of oil supplies or a substantial increase in oil prices could shift consumer demand more toward small cars and depress total vehicle sales due to the adverse effect on the U.S. economy as a whole.

In addition, there were substantial differences of opinion expressed by the automobile manufacturers and catalyst vendors with whom the study team consulted. General Motors said they expected to increase per vehicle catalyst loadings by 10-15% in order to improve the in-use emissions performance of their cars and trucks. Ford, however, expects to leave their per vehicle catalyst loadings essentially unchanged. Johnson Matthey, the largest supplier of automotive catalysts, anticipates significant reductions in total PGM loading will be possible in the immediate future.

Johnson Matthey's rationale for the feasibility of reducing total PGM loadings indicates just how complicated it is to forecast future PGM use accurately. Johnson Matthey expects palladium prices to rise sharply due to reduced exports from the Soviet Union. They also expect reduced rhodium prices due to recent reductions in rhodium usage in glass and nitric acid manufacturing which were achieved in response to the increases in rhodium prices. Johnson Matthey believes that changes in prices and new catalyst formulations will make it economically feasible to slightly increase rhodium usage in 3-way catalysts while reducing the use of platinum and palladium. The net effect could be reductions in total PGM use of about 50%. If Johnson Matthey's speculation is correct, and if automobile manufacturers are able to reduce

PGM consumption by increasing rhodium use, then future PGM demand will be significantly less than the estimates based on our "consensus" opinion.

Another factor affecting future PGM use for automotive emission control is expected changes in emission standards. Based on previously published proposals and discussions with EPA staff, the following changes in the motor vehicle emission control program are anticipated:

- Standards controlling the emissions of light trucks to the same level of stringency as the current passenger car emission standards by 1985 or 1986;

- Standards requiring the catalytic control of heavy duty gasoline engine powered vehicles for trucks up to 16,000 pounds GVW by 1987 or 1988;

- Standards requiring the use of trap oxidizer systems for particulate emission control (some of which will contain catalysts) on about half of the Diesel-powered passenger cars and light trucks beginning in 1987;

- Standards requiring the use of trap oxidizer systems on about half of the Diesel-powered California cars and light trucks beginning in 1986;

- Standards requiring the use of trap oxidizer systems on virtually all Diesel-powered California cars and light trucks beginning in 1989;

- Standards requiring the use of trap oxidizer systems on all heavy duty Diesel engines by about 1990; and

- Standards requiring either increased durability or reduced emissions from catalyst equipped passenger cars and light trucks sold in California beginning in 1987.

In addition to these anticipated changes, there are other changes to the emission control program which would affect PGM demand that were considered possible but unlikely by the study team. These changes include 1) catalyst forcing standards for all heavy duty gasoline engines, 2) catalyst forcing standards for large motorcycles, 3) reduction of the federal passenger NOx emission standard from 1.0 to 0.4 grams per mile.

The estimated per vehicle PGM usage changes associated with future changes in the motor vehicle emissions control program were determined based on a literature review and consultation with vehicle and engine manufacturers. Appendix 3 contains a detailed discussion of the estimates used for future PGM use.

Table 3 summarizes the estimates of future per vehicle PGM use for the various vehicle categories.

Average future PGM loading for passenger cars and light trucks are based on the projected distribution of vehicles by size class from the model developed for use by the Department of Energy's Energy Information Agency by Data Resources Inc. To estimate total annual PGM demand for automotive emission control systems in the future, the DRI model was also used to forecast the total volume of vehicle sales in each of the categories using PGM using DRI's mid-range oil price scenario. Table 4 summarizes the sales forecasts.

Table 3

Future PGM Use Per Vehicle
(troy ounces)

Model Year	Gasoline Fuel --- Cars	Gasoline Fuel --- Light Trucks	Gasoline Fuel --- 8.5-16K Heavy-Duty Engines	Diesel Fuel --- Cars & Light Trucks	Diesel Fuel --- Heavy-Duty Engines
1984	.074	.055	0	0	0
1985	.075	.055	0	0	0
1986	.077	.090	0	.002	0
1987	.080	.095	.200	.024	0
1988	.080	.095	.200	.024	0
1989	.081	.096	.200	.026	0
1990+	.081	.097-.101	.200	.026	.400

Table 4

Future Vehicle Sales Estimates
(1000's)

Model Year	Gas Cars*	Gas Light Trucks*	8.5-19K Heavy Duty Engines Gas -- Diesel		Diesel Cars & Light Trucks	Heavy Duty Diesel Engines
Mid Sales/PGM Use Scenario:						
1984	9,746	2,470	NA		NA	NA
1985	10,410	2,753	NA		NA	NA
1986	10,600	2,807	NA		826	NA
1987	10,645	2,747	328	NA	1,016	NA
1988	10,286	2,583	307	NA	1,098	NA
1989	10,240	2,542	304	NA	1,212	NA
1990	10,388	2,578	304	167	1,359	302
1991	10,876	2,833	332	196	1,700	314
1992	10,860	2,828	329	211	1,943	322
1993	10,761	2,784	324	225	2,168	330
1994	10,625	2,732	315	236	2,379	345
1995	10,468	2,664	304	247	2,576	362
High Sales/PGM Use Scenario:						
1995	12,691	3,349	392	214	1,238	384
Low Sales/PGM Use Scenario:						
1995	8,394	1,184	251	246	3,859	337

Table 5 shows the estimated future PGM use in automotive emission control systems using the per vehicle PGM use estimates from Table 3 in conjunction with the sales forecasts from Table 4. Also shown in Table 5 is a rough estimate of future chromium use. The forecast is based on the assumption that all vehicles using PGM, except those using heavy duty Diesel engines, also use 1.7 pounds of chromium for the containers and connecting pipes associated with the use of the catalysts. This is the approximate amount of chromium needed for a fleet of all monolithic catalyst vehicles which are about 75% inline engine equipped. Heavy duty Diesels are assumed to use twice as much chromium as lighter vehicles.

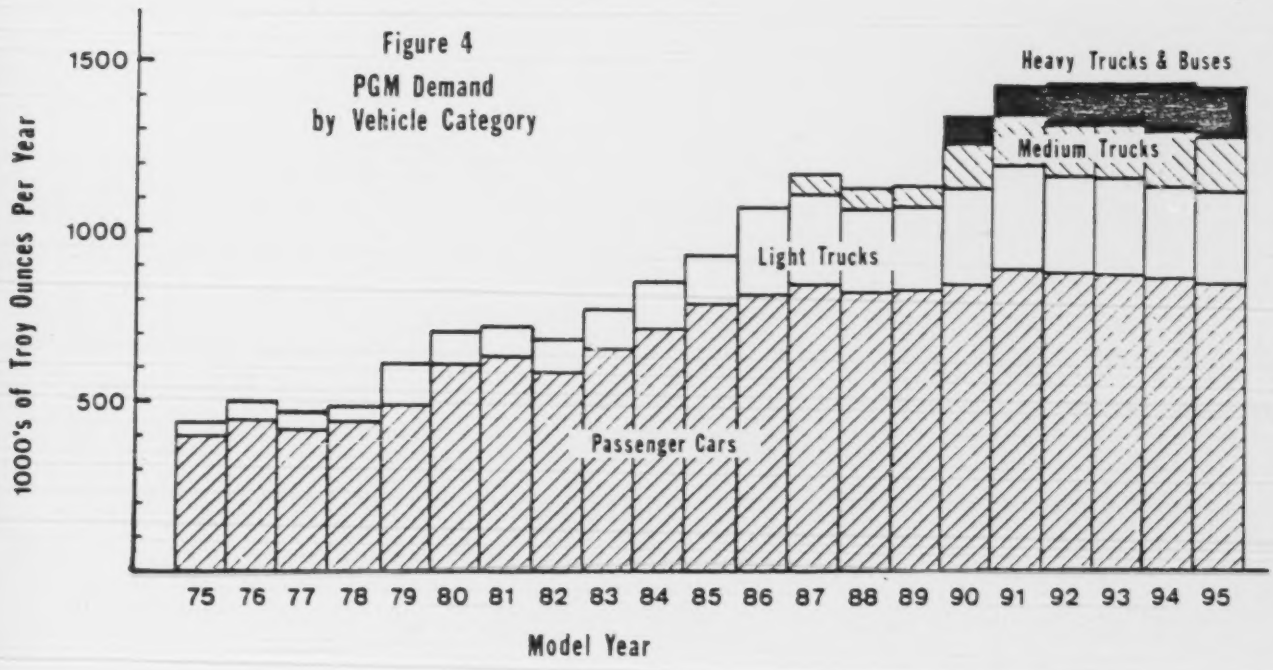
Table 5

Future Consumption of PGM and Chromium in Automotive Emission Control Systems

Model Year	PGM Consumption (1000's of troy ounces) Pt	Pd	Rh	Total	Chromium Consumption (tons)
1984	591.9	193.4	67.3	852.6	10,384
1985	656.1	203.9	76.2	936.2	11,189
1986	772.0	201.3	96.4	1069.7	11,396
1987	859.1	205.2	107.7	1171.8	12,094
1988	836.2	184.3	107.3	1127.9	11,666
1989	851.8	170.0	110.3	1132.1	11,638
1990	1008.4	216.4	116.2	1341.1	12,654
1991	1076.7	231.9	123.1	1431.8	13,524
1992	1080.9	235.1	122.3	1438.2	13,646
1993	1080.8	236.5	121.0	1438.4	13,654
1994	1074.1	237.2	118.6	1430.0	13,620
1995	1065.3	237.9	116.0	1419.2	13,551

As shown in the table, PGM use in emission control systems used on new vehicles is projected to reach 1,000,000 troy ounces per year by 1986 and increase to 1,400,000 troy ounces per year by the early 1990's. Chromium use is projected to reach 11,000 tons per year by 1985. Annual use of chromium is projected to increase to between 12,600 and 13,600 tons per year in the 1990-1995 time frame.

Estimated future PGM consumption in automotive catalysts is illustrated graphically, along with historical consumption trends, in Figures 4 and 5. Figure 4 shows PGM use by vehicle category. It is apparent from this figure that the growth in PGM demand from the mid-1980's to the mid-1990's is principally due to new regulations which are forecasted for medium duty and heavy duty vehicles. Figure 5 shows PGM use for each catalytic ingredient, platinum, palladium, and rhodium.



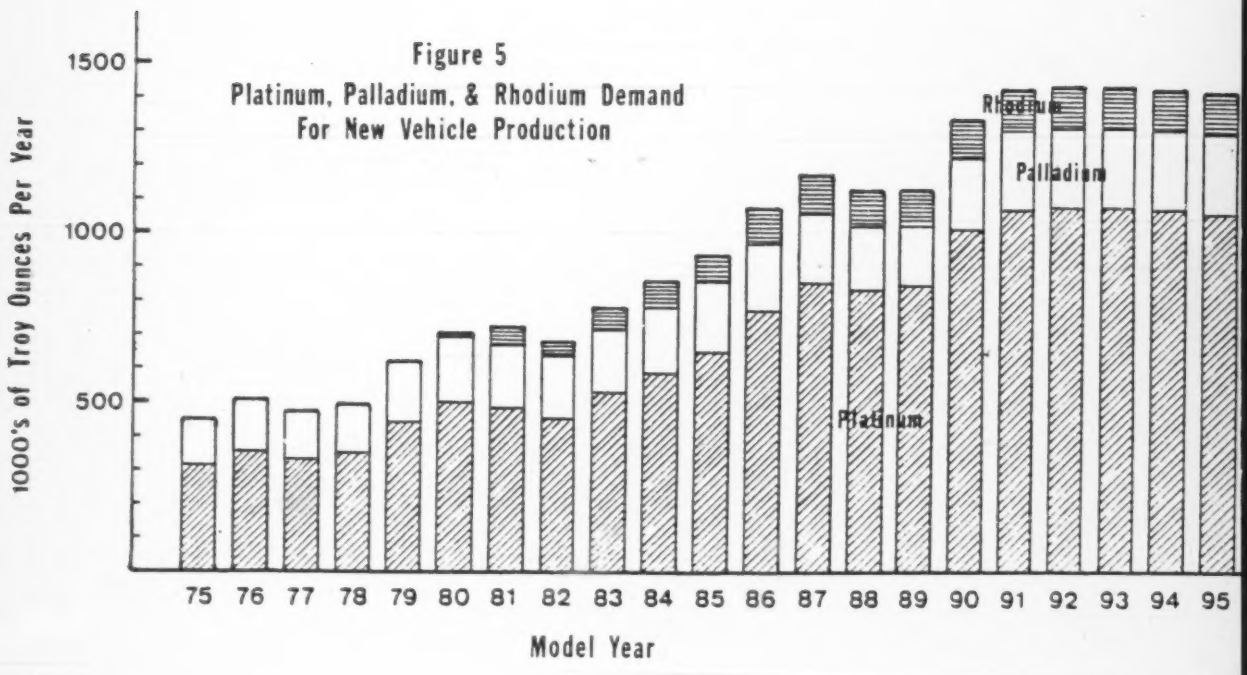


Figure 5
Platinum, Palladium, & Rhodium Demand
For New Vehicle Production

The PGM use forecasts shown in Figures 4 and 5 are based on a "mid-price" forecast for oil. This forecast assumes reasonable availability of imported oil and a healthy economic climate. However, it should be recognized that the future use of PGM and chromium in automotive catalysts can be significantly affected by oil prices and the economic climate in general. Higher oil prices would encourage the production of smaller, more fuel efficient vehicles and a greater fraction of the fleet would be Diesel powered. In addition, higher oil prices are likely to slow down the economy and result in depressed vehicle sales. Lower oil prices would have the opposite effect.

Under a high oil price scenario, the demand for PGM in 1995 is projected to drop by 22% from 1,419,200 troy ounces per year to 1,103,200. Under a low oil price scenario, the demand for PGM in 1995 is projected to increase by 18% to 1,671,700 troy ounces per year.

Section 5

RECYCLING

Since the introduction of catalysts on production automobiles in 1975, precious metal refiners have been interested in using recycled catalysts to augment their PGM sources. There are three phases of PGM recovery associated with catalyst production and use: unused material that failed production specifications; rejected and damaged catalysts from operational vehicles; and spent catalysts from scrapped vehicles. The third category represents the largest future supply of PGM. This section briefly reviews the structure and economics of the dismantling/recycling industry and develops estimates of the volume of PGM potentially available through this network.

Structure of the Recycling Industry

They used to be called junk dealers; now they are known as automobile recyclers. The growing sophistication of this industry will be an important determinant of the volume of PGM it supplies to precious metal refiners. The Automotive Dismantlers and Recyclers Association (ADRA) estimates that in a normal scrappage year (the last normal year was 1979), approximately 10 million vehicles are "detitled" and 9.2-9.4 million vehicles enter the scrappage network. Approximately 70-80 percent of these vehicles move through the 11,000 dismantling yards in the U.S. The remaining 20-30 percent is abandoned, exported or dumped directly into the scrap iron and steel industry where vehicles are either crushed,

baled and eventually either sheared or shredded. Unless catalysts are removed from vehicles prior to entry into this portion of the scrappage process, recovery is impossible.

Scrap iron and steel dealers have indicated an interest in catalyst recycling. However, the economics of catalyst recovery at this point are such that it is not always cost effective for this industry. This is because a large portion of scrapped automobile hulls (what remains of the vehicle following dismantling) moves through shredders. Snredders are large machines that reduce automobile hulls into fist-sized pieces of metal in less than 60 seconds.

Given the high cost of operating these machines and their high speeds, it is not always profitable to take the time to cut a catalyst out of a body if it requires idling the machine. However, at today's prices, hulls are worth approximately $20, and catalysts fetch $3-4 for pelleted and $2-3 for monolith. Thus, a catalyst can represent 10-20 percent of a hull's value and still not substantially alter the industry's recovery rate.

The primary source of recycled catalysts lies within the dismantling industry. The bulk of scrapped vehicles (70-80 percent) move through this industry before reaching scrap iron and steel dealers and their shredders. As an industry, dismantlers routinely remove cores, such as alternators, starters, air conditioning compressors and carburetors. At $2-4 per unit, catalysts are often worth more than batteries, calipers, wiper motors and brake shoes removed on a regular basis. This is the industry that precious metal refiners have targeted for the development of adequate catalyst collection channels.

To date, efforts to take advantage of the organization existing within the recycling industry have been only

partially successful. According to an ADRA poll of a representative sample of its membership in 1980 (when platinum was valued at about $1000 a troy ounce and spent catalysts were worth $20 a piece), only 29 percent of the respondents reported any recycling of catalysts. A 1981 survey of a representative sample of ADRA's membership conducted by Arthur D. Little indicated that approximately 88 percent of the respondents were stockpiling catalysts. It is difficult to extrapolate surveys of ADRA's membership to the rest of the industry because ADRA represents a relatively small percentage of the industry (less than 20 percent). Nevertheless, it is the only survey data available and it indicated a large upswing in catalyst recycling efforts during a time of high PGM prices. Recent telephone conversations with an admittedly unrepresentative sample of dismantlers and scrap dealers indicates a lower level of enthusiasm than displayed in the 1981 survey. Under today's relatively depressed prices for platinum ($500 a troy ounce) and spent catalysts ($2-4), the economic incentive has been substantially reduced. No survey of ADRA's members has been conducted since 1981. Precious metal refiners are openly optimistic about the growing size of the market because of the growing volume of scrapped vehicles which have catalysts and are actively organizing supplier networks.

The precious metal refiners claim that this growth is derived from increased awareness of the value of converters to dismantlers (if an established network for battery recycling has been established where batteries are worth a dollar a piece, why can't a similar system be developed for catalysts with a substantially higher value), and the growing volume of scrapped vehicles which have catalysts. The recycling industry for catalysts consists of four basic components: dismantlers, collectors, decanners and refiners.

Dismantlers

Dismantlers have developed systematic procedures to remove and store converters. One standard procedure is to cut the catalyst out while dismantling the transmission, rear axle and drums. At that point, the extra couple of minutes required to separate the unit from the vehicle generates a $2-4 profit. The larger the quantity of units collected for sale, the greater the dollar value per unit. At first this appears to contradict traditional economics which dictates that a discount is provided for volume. However, because refiners are trying to assemble economic volumes for recovery, a premium is paid for larger volumes of material. When a sufficient number of catalysts has been collected, they are sold to collectors. Usually a minimum of 50 to 100 is required.

Collectors

Collectors buy and sell whole catalysts. Their purpose is to accumulate small lots within a particular region, and sell larger lots at higher prices to decanners. Often, collectors have regular truck routes to purchase catalysts from dismantlers and, in some cases, from shredding yards.

Decanners

Decanners purchase large lots of whole catalysts, and separate the catalyst from the housing. The primary method of decanning is a guillotine device that shears the cannister in half. The pellets and honeycombs are packed separately in 55 gallon drums. Due to the low nickel content and accumulated impurities, the 409 stainless steel used in the converter housings has a low market value; it is currently priced at $110 per ton. Nevertheless, it represents an additional source of value to the decanner.

The quality of catalyst material sold to refiners, as well as the volume, plays a major role in determining the price paid to decanners. Decanners are cautioned not to include contaminated units. Pure white catalysts indicate burn out and loss of the PGM coating. Catalysts coated with lead and oil are also undesirable in the refining process.

When a sufficient quantity of catalysts are accumulated by a decanner (Johnson Matthey requires a minimum quantity of 3000 lbs. per shipment), a refiner will accept shipment. They require that catalysts meet minimum quality standards for moisture and scrap content. A high moisture content can be hazardous to the refining process, and must be controlled during the storage of catalysts and throughout the recycling process. Scrap content refers to the non-catalyst content of the material supplied, and can include portions of casings and impurities collected either during operation or the recycling process. Johnson Matthey currently allows 2% by weight of moisture and no more than 0.5% of metallic and non-metallic scrap. To ensure that minimum specifications are satisfied, an assay is performed on all catalyst material received. Johnson Matthey quoted the following terms in an article presented in Dismantlers Digest.

- Catalyst purchased based on average PGM content; 0.115 wt % Pt for honeycomb and 0.04 wt % Pt for pellet

- Bonus/Penalty for over/under PGM content; $\pm$ 5¢/lb for every $\pm$ .002 wt % change in pellet and $\pm$ 12.5¢/lb for every $\pm$ 0.005 wt % change in honeycomb

- A portion of the catalyst value (50%) is paid upon receipt of the catalyst at the refinery, and balance upon assay. Terms for assay are 6 weeks for honeycomb and 10 weeks for pellet catalyst.

Refiners

Refining is the last step in the recycling process. Refiners basically use an acid leach (aqua regia) to dissolve the PGM from the alumina support. The PGMs are then precipitated and purified. Sebastian Musco of Gemini Industries, Inc., estimates that approximately 90 percent of the PGM contained in the material delivered to the refiner is recovered.

At present there are two primary precious metals refiners operating in today's market - Johnson Matthey and Gemini Industries. Johnson Matthey has a recycling facility in Southern New Jersey, and Gemini is located in Southern California. Several smaller specialty refiners process spent catalysts as part of either copper or nickel recycling; however, they represent very small portions of the market.

Projected Recycling Volume

The methodology used to forecast the demand for PGM in future model years also was used to estimate the volume of PGM that would be available for recovery through the recycling industry. Stated briefly, an inventory of demand for PGM by model year and vehicle category was developed. Standard scrappage curves that relate vehicle survival rate to the age of the vehicle were used to estimate the number of vehicles scrapped each year, as well as the volume of PGM contained in these vehicles. Specialized scrappage rates were used for each category of vehicles to reflect differences in service and durability requirements by vehicle type.

To evaluate potential fluctuations in the market, three recycling scenarios were created: high, mid, and low. The

high PGM consumption, and related scrappage scenario, is based on a low gasoline price forecast, high new vehicle sales forecast, a shift towards larger, heavier (higher PGM requirements) cars, and a low Diesel penetration rate. The low PGM scenario envisions a rapid fuel price increase, a shift toward smaller, lighter cars, a high Diesel penetration rate and a low sales forecast. The mid scenario falls in between these extremes and is viewed as the base forecast. Unless otherwise stated, all of the remaining discussion will refer to the mid scenario.

Table 6 presents a forecast of the distribution of PGM that will be available for recycling. It represents the maximum volume of PGM that will be available for recycling; no assumptions on recovery rates have been included. Automobiles started using catalysts in 1975 and are the largest consumers of automotive PGM. Therefore, passenger cars represent the largest source of PGM to recyclers. Automobiles also have the shortest life span of vehicles on the road. The average automobile will not even reach 100,000 miles in a life time, whereas heavy duty vehicles routinely last for well over five hundred thousand miles or more. The percentage contribution of automobile catalysts to the total PGM available for recycling declines very gradually from essentially 100 percent in the late seventies to approximately 80 percent by 1995. Thus, even though trucks start using catalysts in the early and mid 80's (depending on the vehicle category), because of their longer life span their contribution to supply through recycling remains negligible until after 1990. Nevertheless, the total volume of PGM available for recycling is estimated to grow at an annual rate of 23.1 percent from 1980 to 1990.

Table 7 contrasts the projections of total PGM available through recycling with the percent of new vehicles PGM demand supplied from recycling for three consumption

TABLE 6

ESTIMATED DISTRIBUTION OF PGM FROM SCRAPPED CATALYSTS BY VEHICLE CATEGORY AND CALENDAR YEAR
(10^3 troy ounces)

	Cars	Light Duty Trucks	Medium Duty Trucks	Heavy Duty Vehicles	Pt	Pd	Rh	Totals
'75	0.4	0.0	---	---	0.3	0.1	0.0	0.4
'76	4.1	0.0	---	---	2.9	1.2	0.0	4.1
'77	8.5	0.2	---	---	6.1	2.6	0.0	8.7
'78	19.5	1.3	---	---	14.8	6.1	0.0	20.8
'79	33.2	2.9	---	---	25.7	10.5	0.0	36.1
'80	50.8	4.3	---	---	39.1	16.0	0.0	55.1
'81	73.7	5.8	---	---	56.4	23.1	0.0	79.5
'82	105.6	9.2	---	---	81.3	33.1	0.4	114.8
'83	145.1	12.6	---	---	111.5	45.2	0.9	157.7
'84	193.1	15.0	---	---	146.9	59.1	2.1	208.1
'85	237.8	18.9	---	---	180.9	72.1	3.7	256.7
'86	292.3	23.6	---	---	222.3	87.7	6.0	315.9
'87	346.6	29.1	0.0	---	264.3	102.6	8.9	375.7
'88	396.3	35.6	0.1	---	303.5	115.4	13.1	432.0
'89	442.7	45.0	0.2	---	343.0	126.7	18.2	487.9
'90	486.2	55.3	2.3	0.0	382.7	136.3	24.8	543.8
'91	526.4	65.1	4.3	0.1	420.6	144.2	31.1	595.9
'92	561.3	75.7	7.5	0.4	456.6	149.2	39.0	644.9
'93	593.0	87.2	12.1	4.4	495.8	154.0	46.8	696.7
'94	625.8	99.4	17.3	8.3	537.8	158.7	54.3	750.8
'95	656.9	111.5	23.7	14.3	581.6	163.4	61.7	806.4

TABLE 7

ALTERNATIVE FORECASTS OF PGM AVAILABLE THROUGH SCRAPPAGE BASED ON ALTERNATIVE SCENARIOS OF PGM DEMAND

	Low Consumption Scenario		Mid Consumption Scenario		High Consumption Scenario	
	PGM Scrapped (10^3 troy ounces)	% of New Vehicle PGM Demand Available From Scrap	PGM Scrapped (10^3 troy ounces)	% of New Vehicle PGM Demand Available From Scrap	PGM Scrapped (10^3 troy ounces)	% of New Vehicle PGM Demand Available From Scrap
1975			0.4	---		
1976			4.1	0.8		
1977			8.7	1.8		
1978			20.8	4.2		
1979			36.1	5.8		
1980			55.1	7.8		
1981			79.5	11.0		
1982			114.8	16.8		
1983	158.9	22.9	157.7	20.5	159.0	18.8
1984	208.9	27.2	208.1	24.4	210.2	22.1
1985	256.9	31.0	256.7	27.4	259.9	24.9
1986	313.9	33.4	315.9	29.5	321.5	26.6
1987	371.0	36.3	375.7	32.1	384.5	28.9
1988	423.5	43.5	432.0	38.3	445.1	34.5
1989	474.4	48.9	487.9	43.1	506.7	39.0
1990	523.1	44.9	543.8	40.5	570.7	37.5
1991	566.7	46.1	595.9	41.6	631.9	38.6
1992	604.7	49.4	644.9	44.8	692.1	41.7
1993	645.4	53.6	696.7	48.4	755.5	45.4
1994	686.0	57.8	750.8	52.5	823.1	49.3
1995	728.2	66.0	806.4	56.8	892.9	53.4

scenarios. Not surprisingly, the low consumption scenario provides the best coverage of new vehicle demand due to the relatively low vehicle sales rate and the shift toward smaller, lighter cars. The high consumption scenario, with rapidly increasing sales and a shift towards large cars, displays the lowest percentage of new vehicle PGM demand coverage.

Under the mid-price scenario, the relationship between the demand for PGM in new vehicles and the potential supply of PGM from recycled catalysts is illustrated graphically in Figure 6. As shown in the figure, 50% of PGM demand for new vehicle production is theoretically achievable by the mid-1990's. Beyond this time frame, the percentage of new vehicle PGM demand could increase further. By the mid-1990's, the percent of PGM available through recycling is relatively low because of the increased PGM demand for trucks in the late 1980's and early 1990's. These vehicles will not be scrapped in significant numbers by 1995. If one looks only at passenger cars, the potential effect of recycling is much greater.

Figure 6
PGM Demand vs.
Potential Supply from Recycling

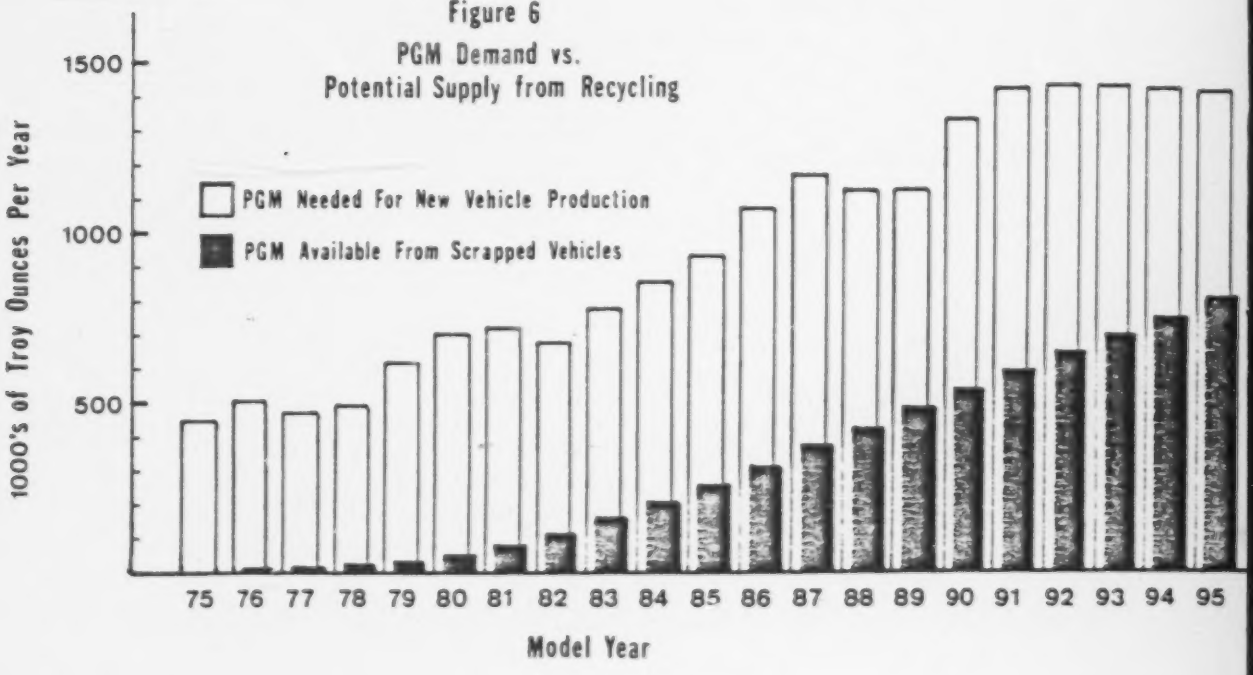

1500
1000
500
1000's of Troy Ounces Per Year
PGM Needed For New Vehicle Production
PGM Available From Scrapped Vehicles
75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95
Model Year

Table 8 compares the volume of PGM required annually in new model passenger cars and the volume that is potentially available through recycling of spent catalysts from these vehicles. Also shown in Table 8 is the volume of PGM that is used on the road by the entire fleet of passenger cars in each calendar year. Over the period from 1980 to 1990, the volume of PGM in use on the road is estimated to grow at almost 11 percent per year. The volume of PGM scrapped from automobiles grows at a rate slightly higher than the 23.1 percent noted in Table 6 due to the higher average age of catalyst vehicles and shorter life span. More importantly, the growth in PGM required in new automobiles is primarily a function of new vehicle sales. Due to the relatively mature nature of the market, the annual growth in new vehicle sales is approximately 2.5 percent over the 1980 to 1990 time frame. The rapid expansion of the PGM scrapped from cars relative to the slow growth in PGM demand for new cars allows the scrap market to represent a large percentage of PGM demand in later years.

The percent of new vehicle PGM demand available through recycling discussed above represents a maximum theoretical potential. As discussed in the earlier section, 20-30 percent of cars do not go through dismantlers, not all dismantlers recycle catalysts, and only 90 percent of PGM is estimated to be recovered in the refining process. Therefore, the share of total PGM demand (for passenger cars only) satisfied through recycling could range from a low of 15 percent (assuming 70% vehicle recovery, 30% catalyst salvage rate, 90% refinery recovery, 656.9 $x10^3$ troy ounces of PGM available for recycling) to a high of 56 percent (80% recovery, 100% catalyst salvage rate, 90% refinery recovery, 656.9 $x10^3$ troy ounces of PGM available through recycling). Given the vagaries of the statistics available describing the recovery rates of the industry, we believe that these assumptions bound the range of recovery currently being experienced.

TABLE 8

FORECAST OF PASSENGER CAR CATALYST FLEET SIZE, VOLUME OF PGM CONTAINED IN THESE VEHICLES, AMOUNT SCRAPPED BY CALENDAR YEAR AND PERCENT OF NEW CAR DEMAND POTENTIALLY SATISFIED THROUGH SCRAP BY CALENDAR YEAR

	Catalyst Fleet Size (10^6)	PGM_3 in Operation (10^3 troy ounces)	PGM_3 Scrapped (10^3 troy ounces)	PGM Used in New Model Year Cars (10^3 troy ounces)	% of New Car PGM Demand Available Through Scrap
1975	8.19	400.7	0.4	401.1	---
1976	17.59	844.3	4.1	447.7	0.9
1977	28.50	1256.9	8.5	421.1	2.0
1978	39.02	1682.6	19.5	445.2	4.4
1979	48.99	2143.5	33.2	494.1	6.7
1980	56.61	2703.8	50.8	611.1	8.3
1981	63.56	3266.8	73.7	636.7	11.6
1982	69.27	3746.3	105.6	585.1	18.0
1983	75.09	4255.3	145.1	654.1	22.2
1984	81.16	4799.0	193.1	716.8	26.9
1985	87.13	5326.0	237.8	784.8	30.3
1986	92.41	5849.9	292.3	816.2	35.8
1987	97.01	6349.7	346.6	846.4	40.9
1988	100.65	6773.2	396.3	819.9	48.3
1989	103.84	7157.9	442.7	827.4	53.5
1990	106.88	7515.6	486.2	843.9	57.6
1991	110.34	7874.8	526.4	885.7	59.4
1992	113.79	8195.1	561.3	881.5	63.7
1993	117.10	8477.3	593.0	875.2	67.8
1994	120.20	8712.5	625.8	861.1	72.7
1995	122.99	8900.9	656.9	845.3	77.7

Neither of the above estimates takes into account the loss of PGM associated with vehicle operation. There appears to be some disagreement about this value; it is reported to range from substantial to much less than 10 percent. A small portion of used catalysts also are being sold as replacement parts for plugged or failed catalysts by dismantlers for as much as $70 a unit. The net result of these factors will be to reduce the volume of PGM for recycling even further. Johnson Matthey estimates that 40% of the current potential supply of PGM for recycling is actually being recycled. They believe, however, that with further industry awareness, this percentage can increase to approximately 70 percent by 1988. A 70 percent recovery rate would allow recycled catalysts to supply approximately 40 percent of the new vehicle demand in 1995. Considering only passenger cars, a 70% recovery rate for scrapped passenger car catalysts would supply approximately 55% of new car PGM demand.

It should be noted that the PGM obtained from recycled catalysts will not necessarily be used for the production of catalysts on new vehicles. Until 1981 and later model cars are scrapped in significant numbers, the majority of the recycled catalysts will contain little or no rhodium. Rhodium is a necessary ingredient in the 3-way catalysts used on 1981 and later model cars. Rhodium usage also is expected to become common in light duty trucks by 1985 or 1986.

Because of the lack of rhodium in the catalysts of most 1980 and earlier model cars, sources other than recycled catalysts will be required for quite some time. Economics may dictate that vehicle manufacturers or catalyst vendors purchase the required rhodium in conjunction with platinum and palladium. In that event, the PGM obtained from recycled automotive catalysts could end up in other applications (e.g., petroleum refining catalysts).

Section 6

ALTERNATIVE TECHNOLOGIES

There are numerous technological alternatives to the use of platinum group metals for automotive exhaust emission control. In fact, virtually all manufacturers currently incorporate non-catalytic emission control techniques in their vehicles. The extent to which non-catalytic control is incorporated determines the amount of PGM that is needed to achieve the vehicle emission standards. No gasoline engine powered passenger cars currently depend entirely on non-catalytic controls; however, differences in the amount of non-catalytic control used in 1982 model passenger cars resulted in approximately a 10:1 range of total PGM loading in catalytic control systems.

The only alternative technology in current use which eliminates the need for PGM entirely is the Diesel engine. However, there are technologies not yet in use which have the potential for eliminating or substantially reducing the amount of PGM used to meet the emission standards.

Background information regarding the evolution of PGM use for automotive emission control and an analysis of the potential for the future use of alternatives to PGM are covered in this chapter.

Evolution of PGM Use in Automotive Catalysts

Auto Exhaust Identified as an Air Pollutant - During the

early 1950's, Professor A.J. Haagen-Smit of the California Institute of Technology experimentally proved that a major cause of air pollution is a series of reactions involving hydrocarbons (HC), oxides of nitrogen (NOx), and sunlight.(26) Haagen-Smit determined that these reactions are responsible for the formation of ozone and other oxidants which are respiratory system irritants and a toxic to plant life. Subsequent to Haagen-Smit's original work, it was determined that hydrocarbon and oxides of nitrogen emissions are also converted in the atmosphere into small particles which scatter light and obscure visibility. It was also determined that in the presence of sunlight and ozone, nitric oxide emissions from the combustion of fuel are rapidly converted into the much more toxic nitrogen dioxide (NO_2). Research also determined that the concentrations of carbon monoxide (CO) in large urban areas were a threat to human health.

Prior to these discoveries, it was commonly thought that air pollution was principally related to visible emissions such as Diesel engine exhaust and trash burning. Since automotive exhaust is usually invisible, exhaust emissions were not considered a significant contributor to air pollution. The discovery that invisible gases are the major cause of air pollution led to government requirements for the control of emissions from motor vehicles. Measurement of vehicle exhaust determined that significant amounts of unburned hydrocarbon, carbon monoxide, and oxides of nitrogen were present. During the 1950's, serious efforts to identify ways of reducing vehicle emissions began.

Early Investigations in Auto Emissions Control - During the mid-1950's, the Automobile Manufacturers Association (predecessor of the Motor Vehicle Manufacturers Association) initiated an organized program of study among the U.S. automobile manufacturers to investigate the feasibility of

reducing automobile exhaust emissions.(27) This and other research performed by automobile manufacturers determined that there are numerous factors related to the amount of exhaust emissions from conventional gasoline engines. Among the factors determined to be related to the quantity of exhaust emissions produced by the engine were air/fuel ratio, mixture distribution, spark timing, combustion chamber geometry, compression ratio, and valve timing. The use of recirculated exhaust gas to control oxides of nitrogen formation was also investigated.

Research was also conducted into the feasibility of treating engine exhaust gas after it has left the cylinder. Techniques investigated included the injection of air into exhaust manifolds to promote the further oxidation of hydrocarbons and carbon monoxide that were not thoroughly burned within the cylinder. Insulated, higher volume exhaust manifolds to increase the temperature and residence time available for such post-cylinder oxidation was also investigated. Afterburner devices involving fuel injection and spark ignition in the exhaust system were also evaluated. Investigations were also performed into the treatment of engine exhaust with catalysts.

One of the first catalysts tested reduced hydrocarbon emissions by 28% when first installed. Performance deteriorated to 14% control after only 1,000 miles of vehicle operation.(27) Poisoning of the catalyst by lead additives in the fuel was thought to be the problem; however, the removal of lead additives was considered impractical, and early catalyst research was focussed on finding a catalyst formulation that would not be poisoned by lead.

The First Auto Emission Standards - The area of the U.S. which has been generally recognized as having the most

serious air pollution problem is the Greater Metropolitan Los Angeles Area. Public concern about the level of air quality in this heavily populated area, combined with the knowledge that techniques were under development to reduce exhaust emissions from motor vehicles, led the California State Legislature to require the development in 1960 of emission standards for motor vehicles.(28)

The concept behind the original California standards was quite different than what is now considered the most reasonable approach to controlling vehicle emissions. Under the early California law, the emission standards applied to "devices" rather than new cars. As soon as at least two devices were shown to be capable of reducing automotive emissions to the level of the standards, then new and used cars were to be equipped with the devices.

The standards adopted by the State of California in 1960 were average exhaust concentrations of 275 parts per million for hydrocarbons and 1.5% for carbon monoxide over a specified, simplistic driving cycle consisting of a variety of idle, steady speed cruise, acceleration, and deceleration modes. These standards were intended to eliminate the smog problem in Los Angeles. They were based on smog chamber experiments showing that an 80% reduction in hydrocarbon emissions should substantially control smog formation. The 275 ppm HC level is approximately an 80% reduction over the emissions of uncontrolled cars using the same test procedure.

California eventually changed its approach to vehicle emission control when it became obvious that automotive emission control is more effectively achieved through an integrated emission control system involving numerous changes rather than with a single add-on device. Manufacturers were required to meet the 275 ppm HC and 1.5%

CO standards on new cars sold in California beginning with the 1966 model year. The Department of Health, Education, and Welfare required manufacturers to meet the same standards on most cars sold in the U.S. beginning with the 1968 model year.

Research and development on catalysts to meet the California standards proved fruitless because no catalyst could be found which was not poisoned by leaded fuel. The removal of lead additives was not seriously considered because auto manufacturers found that they were able to achieve the California standards using less expensive techniques such as leaner carburetion or air injection into the exhaust system.

Development of More Stringent Standards - During the 1960's, it became obvious that the original emission standards developed by California would not be adequate. There were numerous reasons for this, including:

- The significance of evaporative emissions from carburetors, fuel tanks, and gasoline service stations had been underestimated.

- Growth in the population of motor vehicles had not been accounted for.

- Emissions and emissions growth from non-vehicle sources had been underestimated.

- The test procedures were not adequately representative of real world driving and had other deficiencies. They failed to account for "cold start" emissions and allowed manufacturers to employ techniques to meet the standards, such as high idle speeds, which reduced the concentration of exhaust emissions much more than the mass of exhaust emissions.

Researchers from the U. S. Department of Health, Education, and Welfare calculated that approximately 90% reductions in HC and NOx emissions from all sources would be required to achieve healthful levels of air quality throughout the nation. Congress relied on this analysis in developing the Clean Air Act Amendments of 1970. The 1970 amendments required the newly created Environmental Protection Agency to establish standards which would require 1975 and later model cars to achieve 90% lower emissions of HC and CO than 1970 model cars. 1976 model cars were required to achieve 90% lower NOx emissions than 1971 models.

Based on fifteen years of research and development experience in automotive emission control, it was immediately obvious to the automotive industry that the relatively simple changes in design they had incorporated into their vehicles to meet the exhaust emission standards would be totally inadequate. The lead time available to achieve the standards was too short to seriously consider the development of any alternative engines, such as gas turbines or steam engines, that had the potential to meet the emission standards without treatment of their exhaust gas.

Catalytic converters were considered the only possibility by many, however, no catalyst had ever been developed which was not poisoned by lead additives. Automobile manufacturers, led by General Motors, took the position that the production of unleaded fuel was critical to the achievement of the new emission control requirements. EPA took regulatory action requiring the availability of unleaded fuel before the introduction of the 1975 models.

Because of the 1970 Clean Air Act Amendments, a tremendous increase in research and development into exhaust catalysts and many other technological approaches to reducing

emissions occurred. A significant increase in research on alternatives to the conventional gasoline engine also occurred. Some systems using thermal reactors (modified exhaust manifolds designed to enhance post-cylinder combustion of pollutants) demonstrated very low emission levels. However, only systems employing catalysts were able to achieve the required reduction in emission levels without large fuel economy penalties.

Catalyst research and development was now focussed almost entirely on the use of unleaded gasoline, and major improvements in durability were observed. However, all of the catalyst formulations tested demonstrated problems with poor performance during vehicle warm-up, degradation at high temperature, and poisoning by sulfur in gasoline unless they contained platinum group metals. At the existing prices of platinum group metals, adequate performance could be achieved with PGM costs of $10 per car or less. Research into the use of non-PGM catalysts was reduced to a much lower level, and PGM catalysts went into mass production during 1974 for use on most 1975 model cars. Not all cars needed to use catalysts because the 90% reduction standards had been delayed.

The 1975-1979 model year emission standards of 1.5 grams/mile HC and 15 grams/mile CO required about 50% lower emissions than were allowed under the 1972-1974 model standards. Since catalysts were capable of maintaining 60-70% HC and CO control efficiency, the standards were more easy to meet than in prior years, and most manufacturers were able to re-optimize engine calibrations for improved fuel economy. Since 1980, HC and CO standards have been 0.41 grams/mile HC and 3.4 grams/mile CO. However, improvements in the efficiency of catalyst-based control systems have allowed even further fuel economy optimization.

Catalysts used on 1975-1979 model vehicles principally used platinum and palladium as the active ingredients. Such catalysts are effective in controlling HC and CO emissions, but not NOx. More stringent (1.0 gram/mile) NOx standards, adopted in California for the 1980 model year and nationally for 1981 models, resulted in the addition of rhodium to achieve NOx control. With the addition of rhodium and control of the air/fuel ratio to about 14.7:1, HC, CO, and NOx can all be effectively controlled (hence the name "3-way" catalyst).

Maximum NOx control has been demonstrated when rhodium content of a 3-way catalyst is about 15% of the platinum content. However, most manufacturers have attempted to minimize rhodium use because of its relatively high cost. Large manufacturers have attempted to use no more than 1 part rhodium per 19 parts of platinum since this is the proportion in which these two elements naturally occur in the ore being currently mined. This "mine-mix" strategy is an attempt to eliminate cost increases that might occur if rhodium demand significantly exceeded platinum demand.

The need to stay close to a "mine-mix" ratio of platinum and rhodium is now questionable. For example, recent developments in glass and nitric acid manufacturing have reduced the non-automotive demand for rhodium.

Alternatives to PGM Catalysts

The various alternatives to controlling automotive exhaust emissions with PGM catalysts can be separated into two categories: 1) alternative forms of aftertreatment systems (i.e., systems which control emissions after they have left the engine) and 2) basic engine changes. Aftertreatment systems are based on the catalytic or thermal destruction of pollutants. Basic engine changes are intended to reduce the formation of pollutants.

There are two fundamental reasons for the production of emissions from conventional gasoline engines. HC and CO emissions are caused by incomplete combustion of the fuel. NOx emissions are caused by high temperature combustion of the fuel, especially in the presence of excess oxygen.

The conventional gasoline engine is extremely efficient at burning gasoline; however, if only 1% of the fuel used by a car getting 20 miles per gallon passes through the engine without being burned, the car will emit 1.4 grams per mile HC (about 3½ times the 1983 emission standard of 0.41 grams). Incomplete combustion is caused by many factors, including:

- excessively fuel-rich air/fuel ratio
- poor mixing of air and fuel
- misfiring
- poor cylinder flame propagation (flame out)
- flame quenching on "cold" cylinder surfaces

Modifications to engines to minimize these problems, and alternative combustion systems which inherently avoid these problems, can be employed to reduce emissions of HC and CO from the basic engine.

NOx emissions have nothing to do with incomplete combustion. NOx is principally formed by the exposure of nitrogen and oxygen in the intake air to the high temperature associated with combustion at high pressures. To reduce NOx formation, it is necessary to either reduce flame temperature or reduce the concentration of nitrogen and oxygen, or both.

Engine Modifications - "Engine modifications" is a term of art generally used to describe changes to conventional gasoline engines to reduce emissions. There are three principal types of modifications made to control NOx emissions: 1) reduced compression ratio, 2) spark retard, and 3) exhaust gas recirculation. When these techniques are employed in conjunction with rich air/fuel ratios, it is a simple matter to achieve the current 1.0 gram per mile NOx standard. However, the combination of changes necessary to achieve 1.0 gram NOx without catalytic aftertreatment results in reduced fuel economy and very high hydrocarbon emissions (unless a "fast-burn" engine design is employed, as discussed later). High rates of EGR usage slow down the combustion, reduce the stability of the flame, and cause high HC emissions because of localized flame outs.

Engine modifications to control HC and CO emissions include fuel metering systems designed to achieve more uniform mixing of air and fuel, and intake manifold heating devices to minimize the problem of vaporizing gasoline in a cold engine. Lean air/fuel ratios are also able to reduce HC and CO emissions, especially in conjunction with a high energy ignition system to ensure misfire will not occur. However, lean air/fuel ratios are difficult to achieve without combustion stability problems if a lot of EGR is used for NOx control.

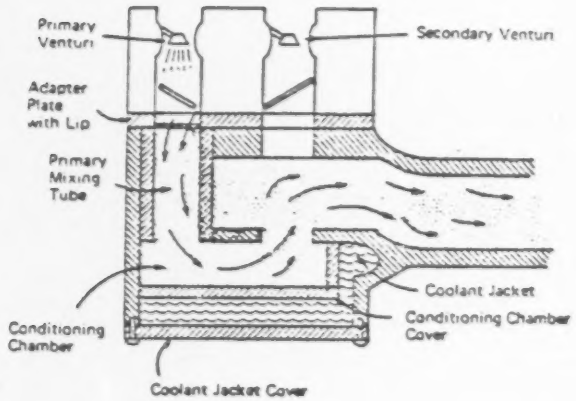
Spark retard is also effective in reducing HC emissions, primarily because it reduces the amount of expansion the combustion products undergo before being exhausted by the engine. The exhaust is therefore hotter and more "post-cylinder" burning of HC occurs.

Very substantial reductions in emission levels have been achieved through the use of engine modifications; however, without thermal or catalytic aftertreatment, no conventional

gasoline engine has demonstrated the capability to achieve the current emission standards (0.41 grams/mile HC, 3.4 grams/mile CO, and 1.0 grams/mile NOx). Using engine modifications only, emission levels of about 1.2 HC, 7.0 CO, and 1.5 NOx have been demonstrated using lean mixtures and improved intake manifolds developed by Ethyl Corporation.(29) A schematic of the Ethyl system is shown in Figure 7. Spark retard was necessary to achieve this level of performance. The fuel economy of a 4500 test weight vehicle using this system was only 11.5 mpg on the city driving cycle. This is approximately 25% lower than the economy achieved with late

Figure 7

Ethyl Turbulent Flow Manifold System



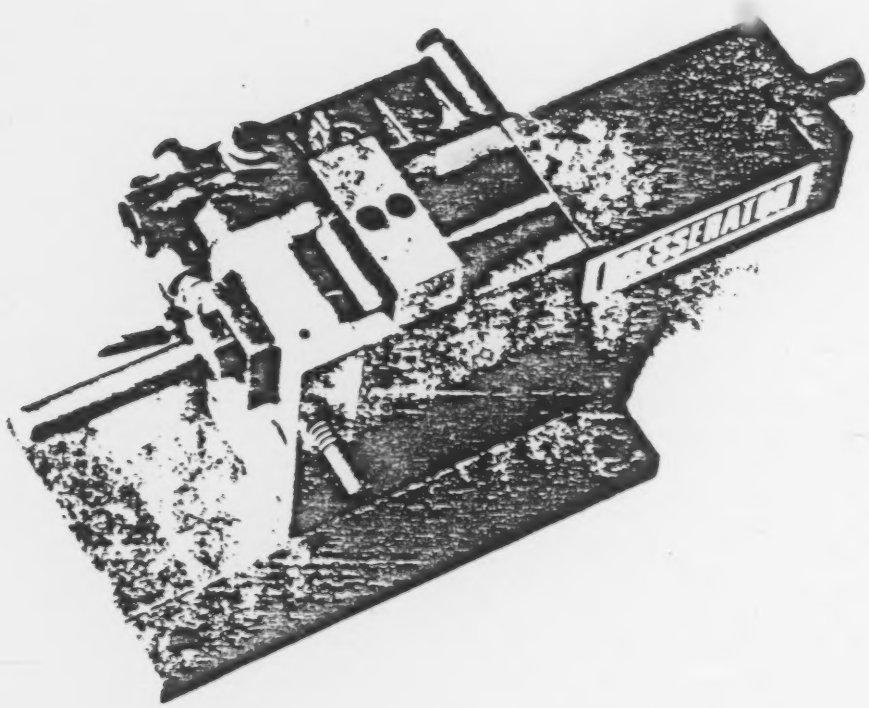
model cars of the same weight which meet the current standards of 0.41 HC, 3.4 CO, and 1.0 NOx. Data available on the Ethyl system indicate that in order to avoid fuel economy penalties it would be difficult to achieve NOx

levels below 2.0 grams per mile unless thermal aftertreatment devices are also used. Use of thermal aftertreatment generally requires increased chromium usage because of the high temperatures which are involved.

The use of "sonic" carburetors developed by Dresser Industries for improved air-fuel mixing in conjunction with very lean calibrations have resulted in emission levels of about 0.8 HC, 5.0 CO, and 2.0 NOx without thermal aftertreatment.(30) Vehicles of 4500 pounds test weight have achieved about 13 mpg, 15% lower than late model cars of the same weight. The Dresser carburetor is shown in Figure 8.

Figure 8

Dresser Sonic Carburetor



The non-catalytic control of NOx emissions can be achieved through a variety of techniques; however, the use of EGR offers the greatest potential to achieve non-catalytic NOx control without fuel economy penalties. EGR is commonly associated with fuel economy penalties because it tends to increase hydrocarbon emissions, and spark retard is then used to control the hydrocarbons. However, EGR itself has no significant effect on fuel economy as long as optimum spark timing is used.(31)

EGR's basic effect is to lower combustion temperature and oxygen concentration through dilution of the air/fuel mixture. The dilution effect also slows down the combustion process. These effects alone would tend to reduce efficiency since maximum thermodynamic efficiency is a function of peak temperature, and theoretical maximum efficiency occurs when the mixture is burned as soon as possible after the piston begins the expansion (power) stroke. However, EGR has other side effects which can offset the efficiency loss associated with reduced combustion temperature and slower flame speed.

First, the addition of EGR to the intake mixture increases the volume of the mixture entering the cylinder for any given load condition other than wide open throttle. This reduces the amount of throttling required and therefore reduces the "pumping loss". In effect, the engine operates more like a Diesel. (The lack of throttling in Diesel engines is one of the principal reasons for their superior fuel economy.) Second, EGR reduces the tendency of an engine to knock. It increases the octane value of the intake mixture. This makes it possible to raise the compression ratio or advance the spark timing for improved economy. Lastly, EGR affects the thermodynamic efficiency of the engine by changing the ratio of specific heats of the intake charge.

The most effective way of increasing an engine's ability to use EGR without degraded fuel economy or high HC emissions is through the use of "fast-burn" combustion chambers. The basic concept behind fast-burn is just what the name implies - to speed up the combustion of the air/fuel mixture. This is accomplished, for example, by inducing a high swirl to the intake charge and using two spark plugs per cylinder to reduce the time required for the flame front to sweep through the entire intake charge.

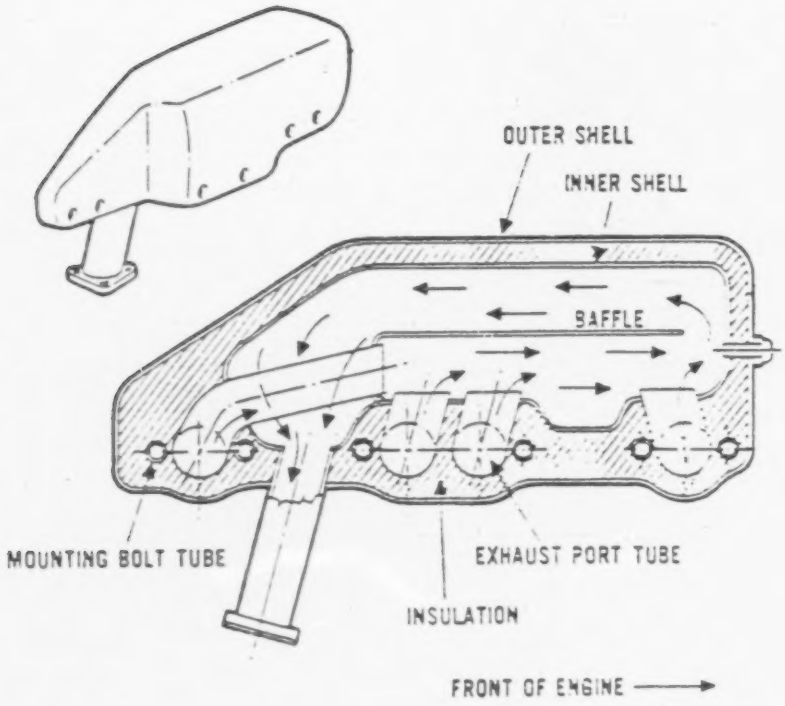
Without fast-burn, EGR in amounts greater than about 10% slows down the combustion process so much that the efficiency increase associated with reduced throttling loss is eliminated. With fast-burn combustion chambers, a mixture with 20% EGR can be burned just as fast as a mixture with no EGR in a conventional engine.(32) Testing of the Nissan fast-burn engine (the NAPS-Z engine) indicates that NOx levels below 1.0 grams per mile can be achieved with fuel economy that is comparable to that achieved on typical late model vehicles which rely on catalytic NOx control.

Hydrocarbon and carbon monoxide emissions with fast-burn engines are not significantly different than those of conventional engines. Thermal or catalytic aftertreatment is required to achieve the current emission standards.

Thermal Aftertreatment - The addition of components and calibration changes to promote the post cylinder oxidation of HC and CO emissions can be extremely effective. Post cylinder oxidation is most efficiently achieved if the time during which the exhaust gas remains at high temperature is maximized. This can be accomplished through the use of relatively high volume, insulated exhaust manifolds. The use of baffling within the manifolds is sometimes used to maximize the length of flow path between the exhaust port and the exit of the exhaust manifold. A typical thermal reactor configuration is illustrated in Figure 9.

Figure 9

Thermal Reactor



The addition of exhaust port liners (to conserve heat) and a lean thermal reactor made it possible to achieve emission levels of 0.4 HC, 5.3 CO, and 1.6 NOx on a large car equipped with the Ethyl Turbulent Flow intake manifold.(29) Without the use of leaded fuel (which increases HC emissions), this system might have the capability to certify at the 0.41 HC standard. However, spark retard was still required to achieve these levels. The fuel economy of a 4500 pound test weight car was only 12.5 mpg in city driving, about 15-20% lower than typical new cars of this weight.

Lean running, sonic carburetor equipped cars using large volume exhaust manifolds to promote thermal oxidation have demonstrated emission levels of 0.41 HC, 4.7 CO, and 1.3 NOx.(30) However, spark retard was also required to achieve this level of control, and the fuel economy penalty compared to current cars was about 25%.

With the use of air injection, EGR, port liners, and insulated exhaust pipes, Fuji (manufacturer of Subaru) has demonstrated emission levels of 1.1 HC, 12 CO, and 1.7 NOx on small cars, apparently without the use of much spark retard.(30) Fuel economy of these cars was comparable to the average late model cars. With a 25% fuel economy loss the same type of system was able to achieve 0.30 HC, 2.9 CO, and 0.72 NOx, levels below the current standards.

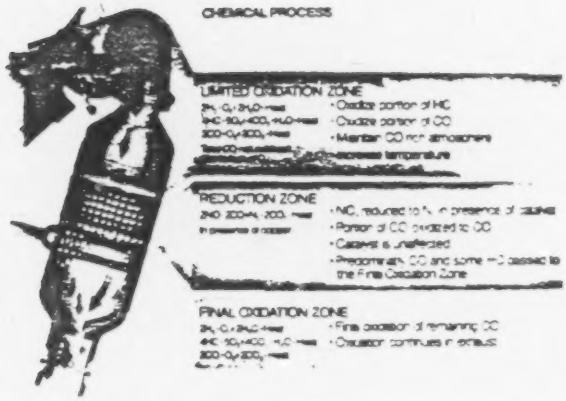
Emission levels as low as 0.1 HC, 2.6 CO, and 0.2 NOx were achieved by Nissan with the use of a rich thermal reactor for HC and CO control in conjunction with a base metal, metallic wire catalyst for NOx control.(30) The system, referred to as the "Questor" system, is shown schematically in Figure 10. Fuel economy of the 2750 pound test vehicle was only 20 mpg, a loss of about 25% compared to current production vehicles of equal weight.

Using a "Lean Combustion System," thermal reactors, and EGR, Yamaha (a developer of engines for Toyota) has demonstrated the ability to reach 0.33 HC, 3.00 CO, and 1.8 NOx with 20 mpg on a 3000 pound test weight car (about 12% lower fuel economy than achieved by late model cars of the same weight).(30) Significantly greater fuel economy losses occurred in an attempt to lower the NOx level further.

Although the use of thermal aftertreatment without catalysts does make it possible to meet the current emission standards, all of the available data indicate an inability

Figure 10

Questor System



to achieve the current emission standards without engine calibrations which degrade fuel economy. In order for thermal aftertreatment to be effective, it is necessary to achieve temperatures high enough to rapidly oxidize HC and CO. This has proven difficult without the use of spark retard or extremely rich air/fuel ratios. Thermal aftertreatment also requires the use of chromium containing steel in the exhaust system because of the high temperatures achieved.

The feasibility of achieving effective thermal aftertreatment without fuel economy penalties will depend on the success in incorporating ceramic components into engines. Ceramic piston crowns and exhaust port liners, combined with insulated, high volume exhaust manifolds, may

make it possible to achieve sufficient temperatures without compromising fuel economy significantly. Progress continues to be made in the development of ceramic components for such applications as turbochargers; however, it is impossible to predict when ceramics may be available for thermal reactors due to the lack of development work in this area.

Without fuel economy penalties, the level of emissions standards achievable using currently available thermal aftertreatment technology is approximately 1.5 HC, 15 CO, and 2.0 NOx.

Alternative Catalyst Technology

Base Metal Catalysts - Many non-noble or "base metal" formulations have demonstrated the ability to catalyze the oxidation of hydrocarbons and carbon monoxide and the reduction of NOx. These materials include nickel, chromium, vanadium, and copper. However, all non-PGM catalysts share three common problems. First, they do not become active ("light off") at as low a temperature as PGM. Second, they are not as stable at high temperature as PGM. Third, they are more easily poisoned by sulfur dioxide from the combustion of sulfur in fuel.

Studies funded by EPA indicate that it would be technologically feasible to reduce the level of sulfur in gasoline by more than 50% with a slight increase in cost.(33) However, scientists from Ford believe that sulfur levels would have to be reduced by almost 99% to avoid the sulfur poisoning problem with base metal catalysts. This level of desulfurization, while probably achievable, is likely to involve extraordinary costs. Ford estimates that the best currently available base metal catalyst formulations would achieve less than half of the control available from PGM catalysts.(5)

Ford believes there is some potential for reducing the PGM loading of catalysts through the use of a low level palladium/base metal oxide formulation. Catalytic NOx control with such formulations may be impossible.

GM's view regarding the capability of the best currently available base metal catalyst formulations is similar to Ford's. GM says that no significant progress has been made in improving the performance of base metal catalysts since the early 1970's.(4) GM also believes that the addition of palladium is critical to the achievement of reasonable performance from base metal catalysts.

The study team could find no information in published technical literature which indicates that the pessimism which auto manufacturers have regarding the potential for base metal catalysts (without PGM promotion) is unfounded. Reductions in high mileage catalyst efficiency of at least 50% would appear to be the absolute best that could be expected from non-PGM containing catalysts in the next few years. Advanced heat conservation techniques and thermal reactors appear to be a superior alternative to PGM catalysts.

PGM Catalysts With Lower Loadings - Ford believes that significant reductions in the loading of PGM catalysts would be possible in the complete absence of lead in gasoline. Although the lead content of the fuel currently used for the certification of new vehicles contains only about 3 milligrams per gallon of lead, EPA regulations allow up to 50 milligrams in commercially available unleaded gasoline. The U.S. average for all commercially available unleaded gasoline is close to 3 milligrams per gallon; however, poor housekeeping practices do result in some gasoline being close to 50 mg per gallon. In order to obtain adequate in-use performance to meet the emission standards on such

fuels, Ford says they must use more PGM than would be necessary to meet the standards if they could be sure that all gasoline contained 3 mg per gallon or less of lead.

GM believes that the loss in efficiency associated with 50 to 75 percent reductions in PGM loading would be substantial.(4)

Alternative Engines

Stratified Charge - The designation "stratified charge" refers to the fact that these engines burn a mixture of air and fuel which is intentionally non-uniform or "stratified". Combustion is initiated in a zone which is rich in fuel and then progresses to a zone which is very lean. The rich zone is either created by injecting a cloud of fuel directly into the cylinder or using a prechamber into which a very rich mixture is carbureted. The prechamber approach is currently used in production by Honda on its CVCC engine. The cylinder fuel injection approach has been employed on engines developed by Ford (Proco) and Texaco (TCCS). These are generally referred to as "open chamber" engines.

Stratified charge combustion offers many potential advantages, including reduced octane requirements, reduced throttling loss (because of the ability to burn overall leaner mixtures), and reduced NOx emissions. The reduced NOx emission potential is associated with the fact that combustion is initiated in a very fuel rich region which has too little oxygen concentration to form NOx efficiently even though the flame temperature is high. By the time the flame progresses into the lean region, temperatures have dropped enough to suppress NOx formation. The Honda, Ford, and Texaco engines have all demonstrated the capability to achieve the 1.0 gram NOx standard (and even the 0.4 gram per mile "research goal") without catalytic NOx control.

Both Ford and Chrysler (working with Texaco) seriously considered mass production of open chamber engines. It was believed that these engines could achieve superior fuel economy due to their ability to run with less throttling and higher compression ratios. However, unless the engines were throttled, their HC emissions were too high to meet the emission standards, even with oxidation catalysts. In addition, the Texaco engine emitted relatively high levels of particulate emissions.

The hydrocarbon emission problem with these engines results from what is referred to as "mid-air quenching" of the flame. The outer edges of the stratified cloud of air and fuel becomes too lean to support combustion, and the flame goes out before every last bit of fuel has been burned. Throttling of the engines reduced the enleanment of the edge of the fuel-air cloud and, more importantly, increased the exhaust gas temperature enough to achieve some thermal oxidation of the exhaust gas in the exhaust manifolds and to achieve rapid catalyst light-off.

The fuel economy losses resulting from the throttling required to meet the emission standards reduced the advantage of these engines to the point where the increased cost associated with their Diesel-type fuel injection systems could not be justified.

Mid-air quenching is not a problem with prechamber stratified charge engines like the Honda CVCC because the main chamber of the engine is filled with an air-fuel mixture that is uniformly distributed. However, because of this uniform distribution of the main chamber mixture, the prechamber engine does not have the fuel economy potential of the open chamber engine. It does have lower HC emissions, and Honda has demonstrated that the current emission standards can be met with their stratified charge

engine without the use of catalysts.(34) However, some thermal aftertreatment is required to meet the current standards, and spark retard is needed to achieve adequate exhaust gas temperatures for effective thermal oxidation of HC and CO. The fuel economy penalty associated with the needed spark retard is not significantly different than for conventional engines meeting the current standards with spark retard and thermal aftertreatment. This is why Honda uses PGM catalysts on its current stratified engines.

Diesel Engine

The principal difference between the Diesel engine and the conventional gasoline engine has to do with the manner in which the fuel is ignited in the cylinder. While the gasoline engine uses spark ignition, the Diesel uses compression ignition. Very high compression ratios (about 21:1 in prechamber Diesels) are used to heat the intake air to the point where it will cause the auto-ignition of Diesel fuel injected into the engine as the piston approaches the top of the compression stroke.

All passenger car Diesel engines currently incorporate a "prechamber" design in which the all fuel is injected into a small chamber connected to the cylinder by a narrow passage. Ignition of the fuel begins as fuel is sprayed into the prechamber and the burning gases and unburned fuel are blown into the engine cylinder where combustion is completed. Prechamber Diesel engines have relatively low NOx emissions for the same reasons that gasoline stratified charge engines do. However, Diesel engines with well-designed injection systems and prechambers do not have the problem with hydrocarbon emissions that stratified charge engines do. Diesels operate at leaner air/fuel ratios which tend to encourage complete combustion, but they have no flame propagation problems because ignition of the fuel occurs

spontaneously at numerous locations because of the high compression temperatures and the low resistance of the fuel to auto ignition. Diesels can meet the current emission standards without thermal or catalytic aftertreatment. Their only significant emission problem is with particulates.

The formation of carbon particulate during combustion is due to the fact that the Diesel uses "droplet" combustion rather than the combustion of a relatively homogeneous mixture of fuel and air as in the conventional gasoline engine. Combustion starts at the boundary between the injected fuel droplet and the hot air in the cylinder, where fuel and air are present in a combustible ratio. As exhaust gases move away from the droplet, more air comes into contact with the unburned fuel and combustion continues. Heat from the boundary of the burning droplet causes pyrolysis of the unburned fuel within the droplet which is not in contact with any air. The pyrolysis forms large amounts of carbonaceous particulate matter, most of which is burned when it eventually comes into contact with the air. However, the particulate is harder to burn than the liquid fuel and a significant amount of it remains unburned.

Emission standards for particulate emissions will require the use of particulate trapping systems on some Diesel cars and trucks beginning with the 1986 model year in California and the 1987 model year in the other 49 states. All Diesel cars and trucks will probably need traps to meet the California particulate standards in 1989. PGM catalyzed traps may prove helpful, however, the use of PGM can be avoided through the use of fuel additives. (see discussion of the potential for the use of PGM catalyzed traps in section 4 of the report.)

Continuous Combustion Engines - Extremely low emission levels without the use of catalytic aftertreatment have been demonstrated for engines which employ "continuous combustion", as opposed to the intermittent combustion which occurs in the conventional gasoline engine. Such engines include the gas turbine (Brayton cycle), the steam engine (Rankine cycle), and the Stirling engine.

The low emission potential of these alternative engines is due to the fact that they utilize relatively low pressure, stratified charge combustion processes. Mid-air quenching of the flame is not a problem because fuel is continuously injected into the combustion chamber, and the flame never goes out.

There is one major drawback to all three of these engines. They represent radical departures from conventional gasoline engines and their production would therefore require substantial, and in some cases complete, retooling. In addition, the manufacturing costs of these engines, especially the turbine and the Stirling, are likely to be significantly greater than for conventional engines. A major problem for the turbine and steam engine is poor fuel economy.

Materials limitations require a tremendous amount of air to be pumped through the turbine engine to keep it from burning up turbine blades. By cooling the exhaust from the combustor with so much air, the efficiency of the engine is degraded. Also, the part load efficiency of the turbine is much worse than the conventional gasoline engine. Since passenger car engines spend so much time at part load, this is a serious limitation of the engine.

Steam engine fuel economy problems stem from the fact that the combustion products are not used directly to run the

engine. Heat from the combustion is first used to make steam, and the steam then actually provides the motive power. Inefficiencies associated with the heat transfer process are substantial.

The Stirling engine also relies on heat transfer to a working fluid (hydrogen gas). However, the design of the engine incorporates the recycling of the energy left in the hydrogen after expansion and efficiency loss is less of a problem. The fuel economy of the Stirling engine is not yet competitive with the conventional gasoline engine.

Previous studies have concluded that mass production of the Stirling engine and the gas turbine engine would be desirable and feasible by 1985.(35) However, the analyses upon which such conclusions were based significantly underestimated the potential for improving conventional engines and overestimated the potential for achieving the theoretical benefits of these alternative engines. The study team concludes that none of the continuous combustion engines are feasible alternatives to the conventional gasoline engine within the 1995 time period. Even beyond 1995, their ability to compete with the Diesel is questionable.

Although the study team's forecast of alternative engines may be inconsistent with some previous studies, our conclusions are consistent with forecasts of future technology use arising out of a recent consensus seeking survey of auto industry executives.(36) In a recent paper regarding future trends in U.S. passenger car engines,(37) participants in the industry survey concluded, "No visible revolution is likely in the system of the engine, but rather a series of micro-revolutions will develop in various subsystems."

These investigators concluded that Rankine cycle (steam) engines for passenger cars would be large, heavy, expensive,

and inefficient. They said no active development is underway. Regarding the gas turbine, inherently poor part load efficiency, poor response, and high cost were noted as major problems. It was concluded that the Stirling engine has good fuel economy potential, but it also suffers from large size, high weight, high cost, and poor response. The authors of the paper concluded that interest in the Stirling engine has been diminished by the improvements which are possible from a much more developed engine, the Diesel.

Most Promising Alternatives

Rich Thermal Reactors - Rich air fuel ratios in conjunction with thermal reactors are the most readily available alternative technology for meeting the current emission standards without PGM. However, fuel economy penalties of approximately 25% are associated with this approach and it must therefore be considered impractical. In addition, the high temperatures associated with the use of rich thermal reactors would significantly increase the amount of chromium that would be needed in the exhaust system.

Diesel Engines - The Diesel engine is the only practical alternative to conventional, catalyst equipped gasoline engines which has the ability to achieve the current emission standards with no fuel economy penalty and no chromium use for emission control. However, the Diesel will soon require the use of chromium for the housings of particulate trap systems. Given the high particulate emissions of the Diesel, these systems will be essential to prevent visibly degraded air quality if the number of Diesel powered vehicles were to be increased significantly.

There are certain economic and institutional factors which limit the extent to which the Diesel will replace

conventional gasoline engines. For example, the first cost of the Diesel engine is somewhat higher than the conventional gasoline engine because Diesel fuel injection systems are more expensive than carburetors or gasoline fuel injection systems. In addition, although Diesel fuel is available throughout the U.S., it sold at far fewer service stations than gasoline. Neither of these factors is considered especially critical by the study team.

A more important institutional factor is that the refining and use of petroleum products in the U.S. has evolved under a situation wherein gasoline for motor vehicles has been the single largest volume product produced from crude oil. Without major changes in refining practices and industrial fuel use, it will not be possible to replace gasoline production with Diesel fuel production. Only under a relative slow transition between gasoline engines and Diesels (covering more than a ten year time period) could refining and industrial fuel use practices be modified economically. Under a faster transition, the price of Diesel fuel would increase dramatically, thereby reducing the demand for Diesel powered vehicles.

Market factors also currently represent a limitation to the replacement of conventional gasoline engines with Diesels. Some motorists will be disinclined to purchase Diesels because of their higher noise level and their lower performance. However, these obstacles can be overcome through continued development of the engine. A major advantage of the Diesel is that the degree to which it can be supercharged is not limited by fuel quality. The development of highly supercharged Diesels offers the potential to achieve gasoline engine performance levels from Diesel powered vehicles.

Lean Thermal Reactors With Fast-Burn - Given additional development efforts, the application of lean thermal reactors in conjunction with improved intake systems, heat conservation techniques, and fast-burn combustion chambers appears to have potential for achieving the current emission standards without significant fuel economy penalties. However, the application of ceramic components, such as exhaust port liners and piston crowns, may be necessary to achieve adequate post-cylinder oxidation of HC and CO emissions without spark retard.

GM, Ford, and Chrysler each told the study team that they do not believe it is yet possible to achieve effective thermal aftertreatment without spark retard. EPA staff believes significant progress can be made in this area. The study team concurs with EPA's views.

Section 7

SUPPLY CURTAILMENT SCENARIOS

In assessing the ability of the automotive industry to respond to the curtailment of PGM, it is necessary to consider the time required to change the design of production vehicles, in addition to the capability of alternatives to PGM catalysts to control emissions.

Lead Time Considerations

The capability of the auto industry to quickly make changes in emission control systems in response to a curtailment of platinum group metal supplies is extremely limited. A considerable amount of "lead time" is required to make significant changes in the design of a motor vehicle unless the changes being made require no significant tooling changes and no "development". Development, in this context, is the process used to adapt and refine a system of proven technological feasibility.

As an example of a change which could be quickly made, the use of additional spark retard for emission control would require no retooling or development efforts. However, there would be adverse fuel economy effects, and additional design changes may be required in order for a manufacturer to maintain compliance with the federal fuel economy standards.

An example of an emission control system change that would require substantial development is the replacement of

catalytic control systems with lean thermal reactors. Although lean thermal reactors can be considered "proven technology", there are numerous changes to automobiles that would be necessary before thermal reactors could be applied to most production vehicles. Examples of the required changes include:

- redesign of prototype thermal reactors to enhance mass production feasibility

- design of engine specific thermal reactors to match the various exhaust port configurations of production engines

- relocation of underhood components and body design changes to provide the space required to fit thermal reactors to various models

- engine specific optimization of fuel metering and spark timing necessary to achieve acceptable driveability

- modification of intake manifolds and fuel metering systems on "problem" engines which cannot achieve commercially acceptable driveability with lean mixtures because of cylinder-to-cylinder distribution problems.

Considerable time would be required to mass produce a fleet of new cars which rely primarily on lean thermal reactors for emission control because the development of production systems is more than a paper exercise. Vehicle systems are too complex for optimum designs to be based entirely on the application of engineering principles and modelling. The development of new systems is an iterative process involving initial design and testing, followed by a series

of redesign and re-testing efforts. This process can be especially lengthy whenever the long term durability of a system change can only be assured through high mileage testing.

Separate from the time required to develop a system change is "manufacturing lead time". If a change requires a significant change in the manufacturing process then lead time may be required to design, build, and install the necessary new tooling. New tooling would clearly be required in our example of a switch to lean thermal reactor emission control systems.

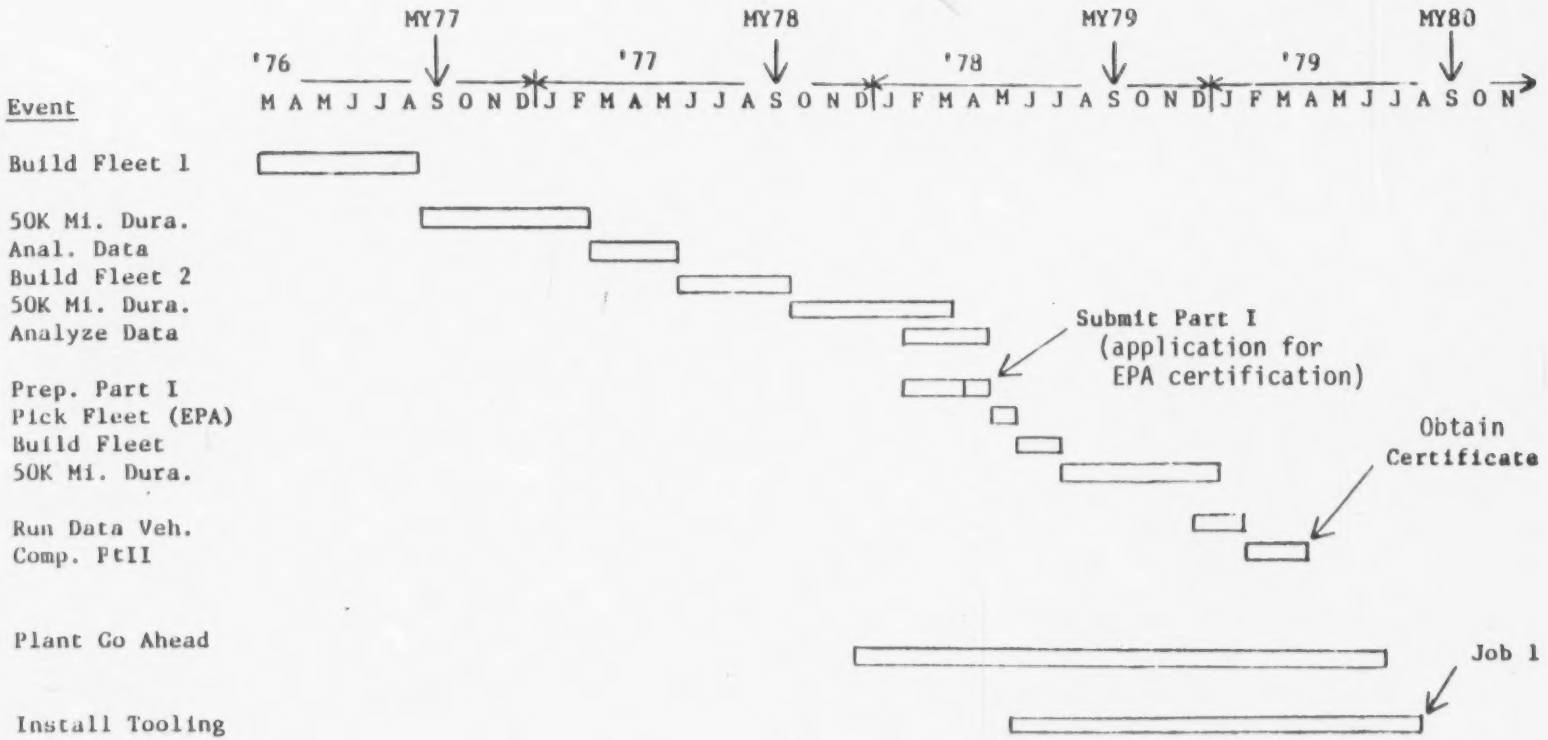
Figure 11 presents an EPA estimate of the lead time required to develop and certify a new emission control system. In this illustration it is assumed that only relatively trivial problems are left to overcome in the development of a particular system. This schedule is optimistic for a change as significant as the replacement of catalytic control systems with lean thermal reactor-based control systems. An additional year of development efforts could easily be required, not including any development of heat conservation techniques that have not been successfully demonstrated already (such as ceramic engine components). As illustrated in the figure, a minimum of 3½ years is required from the start of a development program targeted at certifying some new emission control system that involves significant design changes to the vehicle.

Options for Short Term Supply Interruptions

Given the lead time considerations discussed above, no significant changes in the type of emission control systems used on new vehicles could be quickly made in response to an immediate supply interruption of PGM. In addition, both GM and Ford say the amount of PGM in the "pipeline" would be

Figure 11

Lead Time Schedule for Mass Producing
New Emission Control Systems of Proven Feasibility



exhausted in three to six months. Neither GM, Ford, nor Chrysler have stockpiled substantial amounts of PGM for use in the event of a supply curtailment.

The auto industry could compete for available PGM supplies intended for other uses; however, other uses of PGM are more critical to the continued production of goods. Under a suspension of the emission standards, commercially acceptable motor vehicles could continue to be produced. Loss of PGM to the petroleum, glass, and chemical industries could not be so easily accommodated.

For the purposes of this study, it was assumed that the continued use of PGM in automotive catalysts during an essentially complete curtailment of PGM imports was impractical, regardless of the costs involved. The small amount of platinum required for the oxygen sensors used on most late model cars (about 10 milligrams per vehicle) was assumed to remain available through the use of the limited PGM in the pipeline.

The most reasonable approach for dealing with a complete PGM supply interruption in the short term would be for the government to allow the sale of vehicles that are identical to their certified configuration, except for the replacement of the catalytic converter with a removable section of straight pipe. Such pipes could be produced in sufficient quantities before the limited supply of catalysts was exhausted. (For a chromium supply interruption, in conjunction with a PGM supply interruption, the exhaust pipe connecting the exhaust manifold to the catalyst would also have to be fabricated from mild steel.) Vehicle manufacturers should then be required to recall and retrofit vehicles with catalysts when the supply curtailment has ended. The price of the non-catalyst cars should be increased by an amount sufficient to cover the cost of the

recall campaign and some inducement to ensure a high rate of retrofit.

Based on discussions with GM and Ford, we believe the automobile industry would consider this to be a reasonable approach. GM and Ford representatives were of the opinion that a supply curtailment, if it occurred, would probably be of a relatively short duration (i.e. one or two years). Given the lead time required to redesign emission control systems, the retrofit approach is the only alternative the industry or the report team could conceive of that would not alter the long term effectiveness of the automotive emission control program.

The enforcement of any specific level of emission standards to be applied during a complete short term supply curtailment does not appear to be practical. Because of the high level of model to model variability in non-catalyst emission levels, standards which could be met by most vehicles would have to be set at ten times the level of the current HC and CO standards, and four times the NOx standard. However, average non-catalyst emission levels would be about five times the HC and CO standards and double the NOx standard.

For complete supply curtailments lasting between one and three years, the retrofit approach could be modified to include the recalibration of vehicles for lower non-catalyst emissions. Fuel metering systems could be programmed for somewhat leaner operation to reduce HC and CO emissions. At the expense of some fuel economy loss, spark advance calibrations could be retarded for further control of HC and NOx. Average emission levels approximately equal to the 1977-1979 standards of 1.5 HC, 15 CO, and 2.0 NOx could be achieved under such an approach. However, the standard would have to be applied to the average emissions of a

manufacturer's production because of model to model variability and the lack of lead time to redesign models with relatively high non-catalyst emission levels. Vehicles certified under such an approach would also require recalibration when eventually recalled and retrofitted. Since most systems are now "computer controlled", reprogramming could be as simple as the replacement of a chip within the electronic control unit.

Unless a complete supply curtailment lasted for more than two years, the catalyst retrofit approach would be extremely attractive. In the short term, there would not be a significant increase in emissions associated with such a program because the emissions of the non-catalyst new cars would not be significantly different from the emissions of the older vehicles which are retired from service or driven less as the result of new vehicles entering the fleet. When retrofitted, the automotive emission control program would be back on track, and emissions would be just as low as if the supply curtailment had never occurred.

Under a partial curtailment of PGM supplies, there are two available options which appear most reasonable to the study team. Under the first option, the fraction of each manufacturer's production that is equipped with catalysts could be reduced in proportion to the level of supply curtailment. The vehicles not equipped with catalysts could subsequently be recalled and retrofitted as discussed above.

Under the second option, the loading of each catalyst could be reduced in proportion to the supply curtailment and all cars and light trucks could still be produced with catalysts. Data on the performance of catalysts as a function of loading indicates that a 50% reduction in PGM would produce for less than a 50% reduction in conversion efficiency. (The incremental effectiveness of PGM

decreases as loading increases.) More emission control is therefore achieved by distributing the available PGM among the greatest number of catalysts. The lead time required to produce catalysts with less total PGM content is insignificant.

In the opinion of the study team, the second option would minimize the effects of a partial supply curtailment on the level of automotive emission control, as least in the short term. However, recall and retrofit of the vehicles with more heavily loaded catalysts would still be required if the long term effectiveness of the program were not to be degraded. The inclusion of recall and retrofit would make this option significantly more expensive than the first, since two catalysts would be required for every car.

It should be noted that our conclusion regarding the effectiveness of reduced catalyst loadings is substantially at variance with the opinion expressed by Chrysler. Chrysler told us that 50 or 75% reductions in PGM use would result in "little or no activity" from the catalyst. We note, however, that Chrysler reduced its PGM loading by 41% between 1982 and 1983 without significant changes in emission levels. We do not understand why Chrysler believes that catalytic activity would cease with a 50 or 75% reduction in PGM.

GM said that 50-75% reductions in PGM would result in a "significant" loss of catalyst performance; however, GM said it had inadequate data to provide a quantitative response.

Ford was more optimistic about the feasibility of reducing catalyst loadings without significant activity loss would be significant in any vehicles that were exposed to gasoline lead levels near the .05 gram per gallon limit for unleaded fuel.

Ford believes significant reductions in catalyst loading could be achieved if leaded grade of gasoline were eliminated from the market, because of the resultant effect on the contamination of unleaded fuel that occurs due to pipeline mixing, tank truck contamination, and accidental mixing of leaded and unleaded grades.

Because of the variability in catalyst degradation that would be expected due to a reduction in average loadings, it would not be feasible to require manufacturers to meet any specific emission standards under such an approach. We estimate, however, that the average emission levels of the fleet would increase by much less than a factor of two for loading reductions in the range of 50-75%.

Options for Long Term Supply Interruptions

The response to longer term complete curtailments of PGM would have to consider the capability of base metal catalyst formulations and lean thermal reactor approaches to emission control. At this point it is uncertain as to whether base metal catalysts could be developed which would reduce emissions by at least 50% over the life of the vehicle. Lean burn engines incorporating improved fuel metering and intake systems in conjunction with thermal reactors appear to have significant potential. In conjunction with advanced heat conservation techniques and fast-burn combustion chambers, it may be possible to approach or meet the current emission standards without a fuel economy penalty by using such technology. However, lead time requirements would be substantial. A minimum of five years, and probably longer would be required to develop and mass produce such control systems.

Currently available lean burn, thermal reactor technology appears limited to emission standards of about equal to the

1977 standards (1.5 HC, 15 CO, 2.0 NOx), if significant fuel economy penalties are to be avoided. About four to five years lead time would be required to mass produce such systems.

Under partial curtailment scenarios, much less relaxation in the emission standards would be required. The precise levels of future standards would have to be based on the results of accelerated development efforts on lightly loaded catalysts.

Section 8

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APPENDIX 1

CALCULATION OF HISTORICAL PGM
AND CHROMIUM CONSUMPTION

PGM Consumption

The fraction of each manufacturer's production that was equipped with catalysts was calculated from emission control system descriptions which have been published by EPA.(10,11, 12,13,14,15,16,17,18) Except when the percentage of a particular manufacturer's models using catalysts was 0% or 100%, the catalyst fraction of that manufacturer's total production was estimated based on the relative sales volume of those models (or comparable models) in the state of California (the only sales region for which the study team had access to data on the relative sales volume between the various models produced by each manufacturer). For example, during a particular model year, a manufacturer might have used catalysts on all models produced for sale in California. Because of less stringent emission standards at the federal level, only one of a total of five models might have been equipped with catalysts in the other 49 states. The percentage of a manufacturer's 49-state sales represented by the catalyst equipped model were estimated based on the relationship between the sales of the comparable models sold in California.

When there were differences in catalyst use between California and 49-state models, the percentage of each manufacturer's total sales represented by California cars was estimated based on manufacturers' sales forecasts for California and 49-state vehicles made in applications for certification filed with the EPA. The relationship between 49-state and California sales have been reported by EPA for domestic and import manufacturers separately.(19,20,21)

The validity of the above described method for calculating the fraction of catalyst use by each manufacturer was checked by comparing the composite results to EPA calculations of industry-wide catalyst usage for model years 1978 to 1983 (21). The agreement was within 1%.

In conjunction with the manufacturer specific catalyst loading data described in Section 4, the results of the analysis described above was used to calculate model year specific estimates of average PGM use passenger cars and light trucks for each catalyst equipped vehicle produced by GM, Ford, Chrysler, and AMC, and for foreign manufacturers collectively. The data were then sales weighted to calculate the fleet-wide catalyst use fraction and total PGM consumption for each model year. Historical passenger car sales data for each domestic and foreign manufacturer were obtained from the annual "Market Data Book" issues of Automotive News.(22, 23) Truck sales data for the domestic manufacturers was also based on Automotive News (adjustments were made for the estimated fraction of each manufacturer's total truck sales which were heavy duty vehicles). Relative truck model sales volumes for the foreign manufacturers was based on California sales distributions. The relationship between domestic and import sales volumes for light duty trucks in both California and all 50 states were obtained from information published by EPA.(19,20,21)

Data Summary and Discussion - The results of the historical PGM consumption analysis are summarized in Tables A-1 and A-2. As shown in Table A-1, catalyst usage in passenger cars began at a rate of about 79% in 1975. The average PGM use in each catalyst equipped car was about .062 troy ounces. The level of catalyst usage for GM and Chrysler was almost 100%, Ford was about 75%, while catalyst use on AMC cars and imported vehicles was below 50%. AMC

Table A-1

Historical Vehicle Sales Fractions,
Catalyst Usage, and Catalyst Loadings
for Gasoline Engine Passenger Cars

(Note: Within each element of the matrix, the top number is the fraction of total passenger car sales for the category, the middle number is the fraction of the production in the category that was equipped with catalysts, and the bottom number is the average troy ounces of PGM used in each catalyst equipped vehicle in the category except for the last column which gives the average PGM use for catalyst and non-catalyst vehicles combined.)

Model Year	GM	Ford	Chrysler	AMC	Imports	All Catalyst Vehicles	All Vehicles
	.433	.231	.117	.037	.182	.794	1.000
1975	1.000	.750	.950	.150	.390	1.000	.794
	.050	.059	.047	.050	.070	.062	.049
	.472	.225	.129	.025	.148	.890	1.000
1976	1.000	1.000	1.000	.260	.390	1.000	.890
	.050	.059	.026	.050	.070	.052	.046
	.464	.227	.110	.017	.183	.877	1.000
1977	1.000	1.000	1.000	.260	.390	1.000	.877
	.050	.056	.051	.050	.050	.045	.039
	.477	.229	.102	.014	.178	.897	1.000
1978	1.000	1.000	1.000	1.000	.420	1.000	.897
	.050	.055	.058	.050	.050	.046	.041
	.464	.203	.090	.015	.227	.913	1.000
1979	1.000	1.000	1.000	1.000	.620	1.000	.913
	.050	.079	.067	.050	.050	.051	.047
	.464	.165	.071	.017	.282	.951	1.000
1980	1.000	1.000	1.000	1.000	.830	1.000	.951
	.080	.078	.144	.080	.080	.076	.072
	.445	.163	.088	.016	.288	1.000	1.000
1981	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	.076	.070	.194	.080	.080	.078	.078
	.440	.167	.086	.011	.296	1.000	1.000
1982	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	.076	.063	.116	.080	.080	.077	.077
	.???	.???	.???	.???	.???	.???	.???
1983	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	.076	.055	.116	.080	.080	.076	.076

and most foreign manufacturers elected to use catalysts only to meet the more stringent emission standards in the state of California.

Those manufacturers which used catalysts in 1975 were generally able to achieve significant improvements in fuel economy because the efficiency of the catalysts were more than adequate to provide the additional emission control required between 1974 and 1975. This allowed manufacturers to increase fuel economy, for example, by reducing their dependence on spark retard for the control of emissions from the engine itself.

The interest in achieving the fuel economy benefits of emission control resulted in full use of catalysts by Ford in 1976. AMC went to full catalysts by 1978 when imported vehicles were still below 50%. Full catalyst use by foreign manufacturers was not achieved until 1981, after the federal emission standards had become significantly more stringent.

The average PGM loading for catalyst equipped cars dropped somewhat from 1975 to 1979. The typical catalyst loading for the 1976 to 1979 models was .049 troy ounces, about 22% lower than the first catalysts used in 1975. This drop in loading was made possible due to improvements in catalyst technology and a reduction in the lead content of the fuel manufacturers were allowed to use during certification testing beginning in 1977.

PGM usage for each catalyst equipped vehicle increased in 1980 due to the imposition of more stringent emission standards. Average PGM usage has been fairly stable at about .076 troy ounces per vehicle from 1980 through 1983.

A trend in PGM use which is not apparent from Table A-1 is a shift in the relationship between the amount of platinum,

palladium, and rhodium used in the average catalyst. EPA certification records (21) indicate that from 1975 to 1978, over 99% of the catalysts used on passenger cars were oxidation catalysts. The literature indicates that insignificant amounts of rhodium were used in these catalysts. The active ingredients consisted of about 70% platinum and 30% palladium.

Beginning with a small number of vehicles in 1977, the use of 3-way catalysts containing rhodium has grown substantially. Less than 1% of the catalyst equipped cars used 3-way catalysts in 1977 and 1978. About 3% of the catalyst equipped 1979 models used 3-ways. The 3-way percentage grew to 13% in 1980 when California dropped its NOx standard from 1.5 to 1.0 grams per mile, and most vehicles used 3-way's for catalytic NOx control. With the imposition of a federal 1.0 gram NOx standard in 1981, the percentage of catalyst cars using 3-way catalysts jumped to 85% and it is now approaching 100%.

Detailed analysis of the catalyst specifications for the 1982 models, in conjunction with a literature review and vehicle manufacturer consultation indicates that the domestic manufacturers use platinum and rhodium in a ratio of about 10:1 in those vehicles which incorporate 3-way catalysts. Foreign manufacturers typically use relatively more rhodium and have a platinum to rhodium ratio which averages about 6.5:1. (Some manufacturers use ratios as high as 5:1.) Varying amounts of palladium are used in 3-way catalysts, some manufacturers using none, some using a considerable amount. For the 1982 model year (85% of catalysts being 3-ways), the PGM composition of all catalysts is estimated at 68% platinum, 25% palladium, and 7% rhodium.

Table A-2 shows that the trend in catalyst usage for light trucks is similar to the trend for passenger cars.

Table A-2

Historical Catalyst Use Fractions
and Catalyst Loadings
for Gasoline Engine Light Trucks

(Note: Within each element of the matrix, the top number is the fraction of California catalyst use, the middle number is the fraction of 49-state catalyst use, and the bottom number is the average troy ounces of PGM per vehicle in the category.)

Model Year	GM	Ford	Chrysler	AMC	Imports	All Catalyst Vehicles	All Vehicles
	1.000	1.000	1.000	.200	.120	1.000	.895
1975	1.000	.500	1.000	.200	.000	1.000	.726
	-	-	-	-	-	.050	.037
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1976	.950	.500	1.000	.200	.000	1.000	.708
	-	-	-	-	-	.050	.037
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1977	.950	1.000	1.000	.200	.000	1.000	.830
	-	-	-	-	-	.050	.043
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1978	1.000	1.000	1.000	.200	.000	1.000	.789
	-	-	-	-	-	.050	.041
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1979	1.000	1.000	1.000	1.000	.340	1.000	.875
	-	-	-	-	-	.050	.045
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1980	1.000	1.000	1.000	1.000	.720	1.000	.947
	-	-	-	-	-	.050	.048
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1981	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	-	-	-	-	-	.051	.051
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1982	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	-	-	-	-	-	.052	.052
	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1983	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	-	-	-	-	-	.055	.055

Beginning in 1975, catalysts were used on about 90% of California production and about 73% of 49-state production. The conversion to full catalyst use was somewhat slower than for cars; however, virtually all light trucks were using catalysts by 1981. One difference in the passenger car and light truck PGM trends is that per vehicle PGM use did not increase significantly in 1981. Only a very slight increase is shown in the table because the federal standards for light trucks will not require a similar degree of emission control to that required for passenger cars until 1985 or 1986. The slight increase shown in the table is due to the fact that the California emission standards for trucks were made more stringent in 1981 and increased catalyst loadings were therefore required for the approximately 12% of U.S. truck production which is sold in California.

Another difference between the passenger car and truck PGM use trends is in the relative amounts of the individual PGM constituents used. Rhodium use on cars started becoming significant in 1980 and 1981 when California and federal standards encouraged manufacturers to control NOx emissions catalytically. Since the federal standards do not yet require catalytic control of light truck NOx, 3-way catalysts are only used in significant quantities on California production. By the 1981 model year, 3-way catalyst use was about 3% of nationwide production. It reached about 5% in 1982 and about 10% in 1983. Because of the lower use of 3-way catalysts, the rhodium content of all light duty truck catalysts is only about 1%.

Chromium Consumption

The trend in chromium use has been affected by four factors: 1) vehicle sales volumes; 2) catalyst usage fraction; 3) catalyst type (pellet or monolith); and 4) fraction of "V" configuration engines. The effects of vehicle sales volumes

and catalyst usage fractions are obvious. The effect of catalyst type is due to the fact that the containers for pelletized catalysts are significantly larger than for monoliths. The effect of engine configuration ("V" or inline) is due to the fact that "V" engines require almost twice as much stainless steel tubing to connect the exhaust manifolds to the catalyst.

Based on information obtained from Ford, GM, and technical literature (5,4,8,38), estimates were developed for the chromium content of various engine and catalyst configurations. Each of these manufacturers, and others, use a 409-type stainless steel of about 11.5% chromium content. Estimates for various engine/catalyst configurations are shown in Table A-3.

Table A-3

Chromium Usage in Automotive Catalyst Systems

Component	Stainless Steel (lbs)	Estimated Chromium Content (lbs)
large pellet catalyst	18.3	2.10
small pellet catalyst	11.6	1.34
typical monolithic catalyst	6.7	0.77
exhaust pipe inline engine	6.9	0.79
exhaust pipes "V" engine	12.2	1.40

The chromium usage estimates from Table A-3 were used in conjunction with data obtained from Automotive News regarding the distribution of Vee and inline engines over time (22,23,39,40,41,42,43) to calculate the historical chromium consumption trends. Also factored into the analysis were estimates of pellet vs. monolith catalyst usage by the various manufacturers, based on a review of emission certification documents. The results of the analysis are shown in Table A-4.

Table A-4

Historical Chromium Consumption
in Automotive Catalysts

Model Year	Pounds Chromium/ Catalyst	Gasoline ----- Cars ------ Catalyst Fraction	Sales (1000's)	Gasoline ---- Trucks ----- Catalyst Fraction	Sales (1000's)	Annual Chromium Usage (tons)
1975	2.6	.794	8,186	.746	1,210	9,623
1976	2.4	.890	9,732	.743	1,470	11,705
1977	2.3	.877	10,797	.851	1,190	12,053
1978	2.2	.897	10,859	.814	1,120	11,717
1979	2.1	.913	10,513	.890	2,742	12,641
1980	2.0	.951	8,488	.953	1,943	9,924
1981	1.9	1.000	8,163	1.000	1,664	9,336
1982	1.9	1.000	7,599	1.000	1,913	9,036
1983	1.8	1.000	8,606	1.000	2,109	9,644

APPENDIX 2

ESTIMATION OF RELATIONSHIP BETWEEN VEHICLE WEIGHT AND CATALYST LOADING

An estimate of the relationship between per vehicle PGM use and vehicle weight was initially based on a regression analysis of 1982 model year EPA certification data. Without distinguishing between control technology differences, the average catalyst loading for all vehicles in each weight category indicated the expected relationship between weight and catalyst loading. Average PGM loading increased as vehicle weight increased; however, the r^2 value for a straight line fit to the weight vs. loading data was a miserably low 0.1, indicating extreme scatter in the data and poor correlation.

Because the correlation was so poor, and because the analysis of the data had shown that there were significant differences in catalyst loading as a function of control technology, a more empirical technique was employed to estimate the relationship between PGM loading and vehicle weight. First, all cars equipped only with oxidation catalysts were eliminated from the data base since they are not expected to represent a significant fraction of future production. Next, the "outlier" cars were eliminated from the data base for the reasons described in Section 4. Then, the average PGM loading and average weight was computed separately for cars using multipoint fuel injection and all cars without multipoint injection. Finally, the average PGM loading and weight for these two vehicle classes was used to determine the coefficient of the weight term in the equation: Grams PGM = C x (inertia weight).

This equation assumes PGM loading proportional to inertia weight. This equation form was selected because analysis of the data base indicated that exactly the same type of relationship exists between fuel consumption and weight with a very high r^2 value (0.9). The relationship basically assumes that the amount of catalytic aftertreatment required is proportional to the amount of fuel burned, and therefore the volume of exhaust gas to be treated.

For vehicles with multipoint fuel injection, the relationship between PGM loading (in troy ounces) and weight was calculated to be:

$$PGM = 1.0\ (IW \times 10^{-3})/31.1$$

where: IW = the inertia weight of the vehicle

For other vehicles, the relationship was calculated to be:

$$PGM = 0.8\ (IW \times 10^{-3})/31.1$$

APPENDIX 3

ESTIMATES OF FUTURE PGM CONSUMPTION
DUE TO NEW REGULATIONS

Light Trucks

When all light duty trucks are subject to emission standards of passenger car-type stringency, it is estimated that they will use the same type of catalysts currently used on passenger cars of comparable weight. California's interest in achieving still lower emission levels or improved in-use durability combined with increased focus on in-use durability by EPA is estimated to eliminate the catalyst loading reductions that would otherwise be possible through improvements in catalyst technology. (Higher catalyst loading are an effective means of improving the high-mileage performance of catalytic converters.)

Heavy Trucks

PGM use on heavy duty truck gasoline engines was estimated based on a literature review. Prototype installations of catalysts on heavy duty gasoline engines have used as much as 0.5 troy ounces per engine.(9) However, the prototype engine using 0.5 troy ounces employed a PGM density on the catalyst bed of 50 grams per cubic foot. While some passenger cars still use catalysts with this density, most manufacturers have demonstrated only slight losses in efficiency at about 25 grams per cubic foot. A loading of about 0.25 troy ounces is therefore considered adequate for the level of emission control which EPA is likely to require for heavy duty gasoline engines. If heavy duty truck

engines are tested using the same driving schedule as currently used for light duty trucks (as recommended by GM), then it might be expected that the catalyst loading requirements could be significantly lower. Heavy duty engines are very difficult to control at wide open throttle or near wide open throttle operation. If EPA accepts GM's argument that control of these engines near wide open throttle is not necessary to minimize emissions in metropolitan areas, then the PGM required could drop to between 0.15 to .20 troy ounces per vehicle, the amount the relationship between PGM loading and weight for passenger cars would predict for the test weights that might be expected for the most popular trucks between 8,500 and 16,000 GVW.

For the purpose of projecting future PGM use in heavy duty gasoline engines meeting catalyst forcing standards, the study team assumed the average loading per engine would be about 0.2 troy ounces.

Particulate Emission Standards

PGM use associated with particulate emission standards for Diesel powered vehicles is difficult to estimate. Both catalyzed and non-catalyzed traps are under development. All of the traps under serious consideration depend on filtration by ceramic or metal mesh filters. However, filtration alone is not adequate because the volume of particulate emissions emitted by a Diesel engine is so large that frequent cleaning of the trap is necessary. It is during trap cleaning or "regeneration" that PGM use is beneficial.

The combustion temperature of Diesel particulate is approximately 600°C (1100°F), a temperature which is seldom reached in the exhaust of a Diesel engine. However,

in the presence of a PGM catalyst it is possible to burn the trap clean at a temperature of 350°C (660°F), a temperature which is reached during brisk accelerations and highway cruising speeds.(24) It is also possible to achieve exhaust temperatures above 350°C by retarding the injection timing of the engine or throttling the engine temporarily.

Without the use of a catalyst in the particulate trap, there are two alternatives. The trap can be raised to 600°C through the use of an afterburner. However, the complexity and control problems associated with the installation of an afterburner are undesirable to most manufacturers.

The preferred alternative to the use of a PGM trap are fuel additives. Additives such as calcium, manganese, and lead have proven effective in dropping the regeneration temperature of non-catalyzed traps to about 225°C.(25) These compounds can catalyze the combustion of trapped soot quite effectively. However, they are not effective catalysts if they are merely coated onto the filter itself. The disadvantages of additive-based trap regeneration is that the trap eventually becomes plugged with the residue from the additive, and an on-board system is required for adding the additive to the fuel.

Several manufacturers are working almost exclusively with PGM catalyzed traps, while others (such as GM) are pursuing both additive based trapping systems and PGM catalyzed traps. The study team assumed a 50/50 split between the two types of systems for the future use of traps on light duty vehicles. Based on discussions with Johnson Matthey, it was assumed that PGM catalyzed traps would use a comparable amount of PGM as a conventional catalyst. For heavy duty Diesel engines, the use of additive based systems was considered impractical because of the extraordinary mileage which these engines are driven during their service life.

Additive residues would be a much more significant problem on an engine that may be driven 1,000,000 miles before it is retired from service.

The loading of the PGM traps used on light duty trucks and passenger cars was assumed to equal the loading of conventional catalysts. The loading of the traps used on heavy duty Diesel engines were assumed to be twice that of the catalysts used on heavy duty gasoline engines because of the larger size of the typical heavy duty Diesel engine. All heavy duty Diesel engines were assumed to need traps to meet a 1990 particulate emission standard. Based on an analysis of the particulate emission performance of late model Diesel cars and trucks, it was assumed that half of these vehicles would require traps to meet the federal particulate standards for 1987 of 0.20 grams per mile for cars and 0.26 grams per mile for trucks. Half of the light trucks and cars were assumed to use traps to meet the 1986 California standard of 0.20 grams per mile, and all of them were estimated to need traps to meet the 1989 California standard of 0.08 grams per mile.